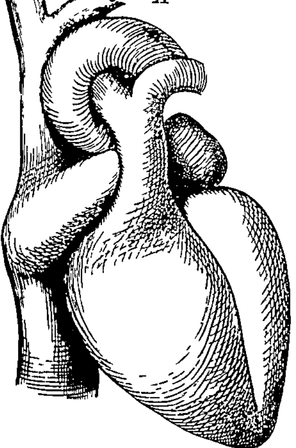
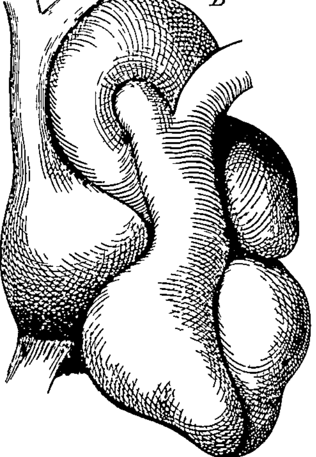
VENOUS RETURN





FRONTISPIECE

FIGURE 1 Illustration of the expansion of atria and venae cavae by the descent of the atrioventricular junction during ventricular systole It can be seen how ventricular contraction might draw blood into the atria by expanding them A = Anterior view of the exposed heart and great vessels during ventricular diastole B = The same view during ventricular systole Drawing by Rollet 1880 (Hermann's Handbook of Physiology) after an original by Henke 1872

VENOUS RETURN

by

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Foreword

It is axiomatic that the heart can pump only as much blood as it receives! Indeed the volume of blood returned to the heart is the basic determinant of cardiac output Since the latter varies enormously under ordinary conditions of daily activity the mechanisms that facilitate venous return have been the subject of discussion for centuries

During the past two decades the application of physical principles the use of hemodynamic models and fragmentary studies on man and animals have brought to light many factors that favor or hinder venous return It has proved difficult however to harmonize differing conclusions and to integrate them into a physiological mechanism applicable to the intact body

The state of confusion that has existed during the past two decades has been partly due to the lack of adequate metering devices applicable to the vena caval systems For this reason a number of optically recording phasic flowmeters suitable for use in venous systems were designed in the Physiological Laboratory of Western Reserve University Medical School Some of these were constructed under the guidance of Dr Brecher and in 1953 there eventuated the high fidelity electronic bristle flowmeter of Brecher and Praglin

The development of new and useful instruments is itself a commendable accomplishment But real progress is made only through their application to cogent problems by competent and discerning investigators Fortunately Dr Brecher possesses both inventive talents and zeal for personal participation in experimental work

The present monograph not only presents a comprehensible comprehensive account of Dr Brecher's contributions but also an excellent historical survey of work preceding his own studies The illustrations are profuse and relevant a large number are original All add materially to the presentation

It will be obvious to the reader that Dr Brecher has applied both synthetic and analytic approaches to the problem of venous return as nature engineered it in the body rather than setting up physical schemes which would or might accomplish the same end

This monograph is the only current one that gives a comprehensive analysis of the determinants of venous return and its adaptation to cardiac output based on experimental measurement of venous flow It should be welcomed alike by laboratory investigators and clinicians who must at all times be alert to avoid procedures that interfere with natural factors favoring venous return

CARL J WIGGERS MD ScD

Preface

It has often been stated that the venous system is the forgotten part of the circulation Although exaggerated this statement is not quite unfounded If the amount of emphasis placed on a subject taught in medical school could be used as a yardstick the venous system would appear to be of minor importance The lecturer usually takes refuge in the consolation that relatively little concrete and noncontroversial information is available about the return flow of blood in the veins

A treatise on this subject appears desirable because no comprehensive work on the venous system has been published since Kenneth J Franklin s A Monograph on Veins in 1937 The present book is not intended to survey the entire field of venous physiology and anatomy since 1937 as Franklin s monograph does up to that date Its scope is more limited It will deal specifically with the *dynamic* aspects of the return flow of blood to the heart These functional aspects have become increasingly the focus of interest in basic research and clinical thinking since it is not the static pressure of blood in a circulatory bed (as reflected by pressure measurements) but rather the *movement* of blood which is of biological importance for the exchange of metabolites and fluids in the tissues For this reason special emphasis will be placed in this monograph on the effect of heart action and respiration on venous flow dynamics

In addition to Franklin s book I wish to refer to other accounts of certain aspects of the venous system whose contents I have not intended to duplicate The reader should consult them for information on the specific problems treated there The basic principles of correlation in the circulatory system are enunciated in the article Venensystem und Kreislaufregulierung (1932) by the late Klothilde Gollwitzer Meier A detailed study of venous flow dynamics with the aid of X ray cinematography is reported by W Bohme in the account Uber den aktiven Anteil des Herzens an der Forderung des Venenblutes (1936) Landis and Horten tine have emphasized the interrelation of venous pressures and fluid exchange in their review on Functional Significance of Venous Pressure (1950) Two books of G E Burch A Primer of Venous Pressure (1950) and Digital Plethysmography (1954), deal with the methods and clinical applications of venous pressure measurements and of plethysmographic flow recordings respectively

I am particularly indebted to all my associates and friends in the Department of Physiology at Western Reserve University Cleveland Ohio where much of the experimental work reported in this book was done Dr Carl J Wiggers was a source of continuous inspiration and helpful criticism while I had the privilege of working in his famous cardiovascular laboratory I wish to thank especially Drs Emil Ritter George Mixter Jr Julius Praglin Charles A Hubay and E Q Adams for the large part they played in the studies of venous flow, and Mr Clyde Bratton Mr Richard Freeman Mr Willard Stires

and Mr Eugene Scott for their technical assistance Several members of the physiology departments at Western Reserve University and Ohio State University have helped in the preparation of the manuscript by their valuable suggestions Many friends in different parts of the world have liberally contributed by lending me originals of illustrations Although all are not mentioned individually I thank everyone

I also want to acknowledge with many thanks the valuable support of the Life Insurance Medical Research Fund, the Cleveland Area Heart Society and the American Heart Association for making this work possible

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Columbus Ohio
January 1956

I Historical Considerations

As early as the third century B C, thought was given to the question of how blood enters the heart At that time the Greek physician Erasistratus is supposed to have stated that the heart acts as a pressure suction pump sucking blood into the ventricles during diastole Ever since that time and even after the days of Sir William Harvey, the opinion has been voiced that the force imparted by the heart to the expelled blood is not sufficient to explain venous return and filling of the ventricles The nature of other forces which bring about the return flow of blood to the heart has been the subject of heated discussion and controversy for centuries Even today opinion is far from uniform

Probably the main reason why knowledge of venous return has not kept pace with our understanding of the other parts of the circulatory system is the lack of adequate methods for accurate measurements of venous flow Each time a new idea and methodological approach was advanced which helped to explain some aspect of venous return it gave a new impetus to investigative endeavors Numerous simple experiments and deductions have been forgotten only to be redi covered by more advanced and complicated methods

Since the effect of the heart s action and respiration on venous return are the subjects of particular interest for an understanding of venous flow dynamics the historical considerations are confined to these problems

Vis a Tergo

The propelling force which is imparted by the myocardial contraction to the blood during its passage through the heart is called the *vis a tergo* This force from behind even after its reduction in the arterioles and capillaries is believed to be sufficient to account for an adequate return flow of blood This view was first clearly expressed by Harvey in 1628 It was quickly accepted by scientists as documented by Lower who wrote in De Corde' (1669) It is an undisputed fact that the return of the venous blood is the result of the impulse given to the arterial blood and not of any attraction by the heart"

Even up to the present the authority of Harvey has greatly contributed to the persistence of the view that the heart acts exclusively as a pressure pump A number of classical experiments are usually quoted (Poiseuille, 1830 Ledderhose 1906) to prove that in the absence of other forces (muscular contractions respiration and hydrostatic differences) blood is adequately returned to the heart by the *vis a tergo*

However these experiments cannot be considered as conclusive evidence that the *vis a tergo* is the sole cause of the return flow of blood in the absence of muscular respiratory and hydrostatic factors If the heart by its contraction and relaxation should in some way or another attract the venous blood it could augment venous return Unfortunately this sucking force cannot be easily distinguished from the pure *vis a tergo* when the effects of respiration the muscle pump or hydrostatic pressure are eliminated

Summarizing

The *vis a tergo* appears to be the main but not the sole force responsible for the return flow of blood

Vis A Fronte During Ventricular Diastole

The force or combination of forces acting from the front to attract blood in the veins towards the heart is called the *vis a fronte* This force may stem from the action of the heart itself or from the action of the respiration Let us first consider the opinions about the *vis a fronte* which may be attributed to the heart

The view of Erasistratus (c 290 B C) and later of Galen of Pergamon (131–201 A D) that the heart is a pressure suction pump was founded mainly on *the assumption that blood was sucked into the ventricles by their active en* largement Galen believed that the heart contained muscles which spread the ventricular walls apart after their systole We are inclined to smile about this "naive misconception ' of Galen, whose opinion determined and confused scien tific thinking for 1300 years up to the Renaissance But was he really so com pletely mistaken? The most recent authority on the subject Guasp (1954) makes a very good (though not experimentally proven) case for the existence of specific musculature in the heart which actively expands the ventricular cavities at the beginning of diastole He states 'The force that expands the ventricles is represented by the intramural conducts and by the muscular *trabeculae* which form the ventricular spongy system In the 2300 years be tween Erasistratus and Guasp opinions have varied and clashed between the two extremes, i e between the adherents of an active diastole and those assum ing a purely passive role of the ventricle in diastole

The older literature was extensively reviewed by Ebstein (1904) Undoubt edly Harvey was the first scientist of modern times who denied the existence of an active diastole when he wrote in 1628 "Likewise, it is not true as commonly *believed, that the heart by its own action or distension draws blood into its* ventricle The father of physiology, Albrecht von Haller (1708–1777), also did not believe that the heart exerted a sucking action On the other hand, Zugenbuhler (1815) and Schubarth (1817) argued that the ventricles must suck blood into their cavities to prevent the formation of an "empty space'

The first experimental approach to the subject was made in 1828 by Wede meyer who inserted a catheter into the jugular vein of a horse He observed during atrial diastole a rise of colored fluid in a glass tube attached to the end of the catheter Wedemeyer interpreted this as a sucking action of the heart on the blood in the caval veins during the diastole of the atria and called it atrial aspiration Donders (1859) believed that Wedemeyer's observation speaks strongly in favor of an active expansion of the heart but that it does not prove it conclusively The idea of an atrial aspiration has not been abandoned even in modern times Based apparently on Wedemeyer s observation, we find in the 1955 edition of Houssay s textbook Human Physiology the statement that the heart asserts a certain sucking effect on the blood of the veins at the beginning of auricular diastole No conclusions as to the action of ventricular

diastole can be arrived at from Wedemeyer's experiments because atrial diastole comprises the period of ventricular systole and beginning of ventricular diastole

Goltz and Gaule (1878) swung the pendulum of opinion strongly to the side of ventricular aspiration They reported that pressures fell during diastole in the left ventricle to −52 mm Hg in the right ventricle to −17 2 mm Hg and in the right atrium to −11 2 mm Hg

In the opinion of most scientists the hypothesis of a distolic ventricular aspiration became untenable after the advent of modern manometry based on the sound physical principles advocated by Otto Frank Von den Velden (1906) Straub (1910) and Wiggers (1928) showed with manometers of high frequency response that Goltz's recordings of negative pressures were caused by instrumental errors Nevertheless the battle continued even in C J Wigger's own laboratory when Katz (1930) observed a marked diastolic sucking action of the ventricle Working in the same laboratory, Cotton (1934) pointed out only four years later that it was Katz's experimental arrangement and not the heart that may have been responsible for the apparent sucking action The latest contributions in favor of an active diastole are from Villa (1954) Guasp (1954) and Cignolini (1954) Though working independently these authors have come to similar conclusions, based on theoretical considerations and inferential evidence

The active dilatation of the heart muscle has been attributed to various forces First some believe that a portion of the myocardium expands the ventricular cavity by a contraction of its muscle fibers at the beginning of diastole The action of these fibers would be antagonistic to those which cause the expulsion of blood from the ventricles (Galen Brauer [1904] Guasp [1954] This view was opposed by Hyrtl who stated in 1855 In the heart there is not a single muscle bundle present which by its contraction could enlarge the cardiac cavities

Second a group of workers represented by Donders (1859) believed that the blood which enters at the end of systole into the coronary arteries seems to cause a slight active expansion of the heart especially of the ventricles ' This view was formulated by Brucke in 1855 (see 1872) and particularly advocated by Luciani (1911) A modification of this hypothesis is presented by Cignolini (1954) based on x ray kymograph studies Third some have attributed the aspiration of the heart during diastole to the recoil of elastic elements or an active de contraction of the muscle Adherents of this view include Magendie (1817) Luciani (1911) Goltz and Gaule (1878) and Villa (1954)

Summarizing

Though the ancient hypothesis of a diastolic aspiration of blood by an expansion of the ventricular cavities has gradually lost ground, several arguments in favor of this hypothesis have never been conclusively proven or disproven under properly designed experimental conditions

Vis a Fronte During Ventricular Systole

Bohme (1936) pointed out that one could consider Aristotle (384–322 B C) as the first who mentioned a process which may affect venous return during ventricular systole Aristotle is credited with the discovery of the *punctum saliens* i e, the observation of alternating cardiac volume changes in the bird

embryo As Benninghof showed cinematographically in 1935, the movement of the atrioventricular junction during ventricular systole in birds corresponds closely to that observed in mammalian hearts

The idea that the contraction of the ventricular muscle during systole could attract blood in the veins toward the heart has appealed to scientists far less than the diastolic aspiration No mention of it is made in the classical cardiovascular literature until Purkinje in 1843 and Nega in 1852 hypothesized that the heart exerts a *sucking action during systole* Purkinje noted that the apex of the beating heart moves relatively little (he called it *punctum fixum)* whereas the atrioventricular junction moves, during ventricular systole, relatively greatly toward the apex (he called the atrioventricular junction the *punctum mobile)* Functionally inclined anatomists who observed form changes of the heart during its cycle became the main proponents of this theory, which has only recently aroused the interest of physiologists The manner in which the contracting ventricle is supposed to draw blood from the veins into the atria is best illustrated by the original drawing of the anatomist Henke They are reproduced in Fig 1 (A and B) He drew these schematic diagrams in 1872 from direct observations on living animals in Carl Ludwig s famous cardiovascular laboratory and from autopsy material

These figures explain better than words the form changes of the heart which suggest a systolic attraction of blood Rollet who produced Henke's drawings in Hermanns *Handbook of Physiology,* stated

'One can see how during ventricular systole the atrioventricular junction approaches the apex which remains almost stationary whereas during diastole the atrioventricular junction returns to its previous position This descent and ascent of the atrioventricular junction is the most conspicuous movement which can be perceived in the acting heart ' He believed that blood is sucked into the atria by the descent of the atrioventricular junction and that the lungs by their elastic pull aid in maintaining the outer contour of the atria

Apparently this hypothesis soon drifted into oblivion since no evidence other than the observation of the heart s movement could be marshalled in support of the systolic suction

However, some interest was maintained by another group of investigators Clinicians and physiologists who attempted to interpret minute fluctuations of air pressure in the respiratory channels as due to changes in the volume of the heart (cardio pneumogram) found in the complex pattern of their tracings certain deflections which could be interpreted as a systolic suction of the ventricles In 1852 Ceradini recorded cardio pneumograms from which he developed formulae for the calculation of cardiac output

The extensive literature on this subject has been reviewed by Hamilton (1930) and Holzlohner (1932) These two authors came independently to similar conclusions Hamilton deduced from human cardio pneumograms that atrial inflow during ventricular systole could be almost as large as the ventricular stroke volume Holzlohner, who used a hot wire anemometer, concluded that "the venous blood inflow becomes stronger than the arterial discharge during the second part of the outflow period of the left ventricle " He later added (1936) that for

The static position of the thorax would be best defined as that assumed during the normal expiratory pause Pfuhl calculated in 1929 from measurements of the total surface area in man that in this position the retractive force of the lungs was 15 to 20 Kg The retractive force acts through the pericardium on the heart It was calculated as 0 48 Kg acting on the entire surface area of the right atrium 1 73 Kg on the right ventricle, 0 51 Kg upon the left atrium and 0 96 Kg on the left ventricle

Following the ideas of Carson Barry and Donders Pfuhl believed that the continuous lung traction is the most important factor for the filling of the atria and ventricles by holding them open When the myocardium contracts part of the energy must be used to overcome the lung traction which is the permanent dilator of the heart chambers The atrial muscle may not contract to the same extent in the closed as in the open chest because lung traction opposes the atrial contraction Continuous lung traction holds the intrathoracic veins and heart chambers open and creates a low pressure in them This causes the blood to flow from the regions of higher pressure outside the thorax into the chest veins and heart

Unquestionably the continuous action of lung traction produces a greater pressure difference between the extrathoracic capillaries and the heart chambers than would exist in its absence such as in open thoracotomy However how much this factor alone contributes to a greater venous return is difficult to quantitate since shortly after opening of the thorax compensatory mechanisms come into play which bring venous return, and thus cardiac output, to nearly the same level as existed in the closed chest The fact that the circulation is well maintained after the chest is opened has caused today s physiologists and thoracic surgeons to minimize the importance of the continuous elastic traction of the lungs on venous return No clarification of the importance of this factor can be obtained until quantitative measurements of venous return in suitable experiments are available

The classical view of the continuous elastic traction of the lungs which dilates the heart chambers and counteracts their complete emptying has been recently supported by Rushmer (1954) who used an entirely different approach He inserted a strain gauge spring device into the left ventricle and measured the transverse diameter of the left ventricular cavity in dogs with the chest open and closed He found that in the closed chest the left ventricular chamber has a greater diameter during systole and at the end of systole than when the lung traction is abolished by opening the chest

Though *static* negative pressure in the thorax tends to hold the heart chambers open it is fallacious to assume that this pressure as such is performing work The energy available from elastic recoil is a potential energy and external work can only be done when this potential energy level is altered Thus kinetic energy can only be released (= work performed) through *changes* of intrathoracic pressure by muscular activity

Summarizing

The continuous elastic traction of the lungs creates negative intrathoracic pressure and thus favors venous return by producing a pressure difference

of the atrial cavities and the descent of the atrioventricular junction during ventricular systole He injected drops of iodopin oil into the jugular vein and showed that during ventricular systole these drops were greatly accelerated in their flow through the superior vena cava He stated "With these observations the proof of the systolic suction attraction (Ansaugung) of the venous blood by the heart appears to be finally established One can *see* that during the time when the *ventricle becomes smaller* while ejecting its content and the *atrium enlarges* in the direction toward the retracting ventricle both venae cavae *decrease in caliber* simultaneously with a remarkable centripetal *acceleration* of their content Since this occurs irrespective of an inspiratory or expiratory position of the thorax and even in the absence of any action from the lungs there can be little doubt that a great active participation of the heart in promoting venous return has been finally proven

It may appear that Bohme solved the problem However, he himself pointed out that his observations were of qualitative nature only By comparing the velocity of iodopin oil drops in the caval veins during ventricular systole and diastole he inferred that 10 times as much blood would flow toward the heart during systole as during diastole Holzlohner and Schonerstedt therefore attempted in 1940 to quantitate with the aid of a flowmeter the amount of blood which flows through the external jugular vein of a dog during ventricular systole and diastole They believed that Bohme s estimates were too high regarding the portion of the blood which passes through the vein during systole

Summarizing

Though relatively late in its conception the theory of an attraction of venous blood by the contraction of the ventricle has gained greatly in favor It is supported by rather inconclusive evidence derived from anatomical observations cardio pneumograms and venous and atrial pressure pulses It is strongly supported by qualitative evidence from x ray cinematographic studies

Static Negative Intrathoracic Pressure

One must distinguish between two effects of the respiratory apparatus on venous return (1) The static effect of the continuous negative intrathoracic pressure and (2) the dynamic effects of changes in intrathoracic pressure which occur during spontaneous respiration artificial respiration, controlled respiration and various voluntary and involuntary respiratory maneuvers Under normal physiological conditions static and dynamic effects are integrated in their action on the return flow of blood but they can be separated theoretically and experimentally

For many years the opinion prevailed that the *permanent* elastic traction of the lungs is one of the most important causes of venous return by virtue of the production of negative intrathoracic pressure This view goes back to the early part of the eighteenth century when the work of Carson Barry Ludwig and Donders on the tractive force of the lungs moved into the center of attention among physicians In the work of Carson (1820) and Barry (1826) the continuous effects of lung traction upon venous return was distinguished for the first time from the intermittent effects produced by respiratory movements

though his results were only of a qualitative nature, the ingeniously conceived experimental arrangement embodies the principles of the more recently developed velocity flowmeters

The results of Barry have given rise to a number of questions which have stimulated investigators up to the present (1) Why is the blood flow through the jugular vein during inspiration accelerated only when the horse is lying down? (2) Why did Barry not observe changes of blood flow synchronous with respiration when the horse was standing? (3) What caused pulsatile flow of blood of a higher frequency than the arterial pulse? (The answers are discussed on pp 66 and 71)

The classical view concerning the effect of respiratory movements on venous return is best stated by Donders (1859) During quiet inspiration and expiration blood is always drawn toward the thoracic cavity with stronger inspiration it becomes strongly attracted by the chest cavity only in strong expiration is it pressed out of the thoracic cavity "

Donders thus introduced the concept of the respiratory pump It was based on the logical deduction that blood flow toward the heart must increase when the intrathoracic pressure becomes lower during inspiration Since no experimental evidence was presented by him his opinion was subjected to criticism by others as discussed by Henderson and Barringer (1913 a, b) Volkmann (1850) Mosso (1878) and Ledderhose (1906) believed that the increased venous return during inspiration was cancelled by a corresponding reduction of venous return during expiration and as a net result respiratory movements would not increase venous return A number of authors argued that the return flow of blood from the inferior and superior venae cavae either differed greatly or were even opposite in direction during the respiratory phases

T Lewis (1908) and later Eppinger and Hofbauer (1911) thought that inferior caval flow decreased during inspiration On the other hand de Jager (1883) suggested that it must increase on account of the increase in abdominal pressure Franklin (1937) takes the view that inferior vena cava flow may be variable as the result of inspiration Seely (1948) could not find any evidence from intracardiac pressure measurements that inspiration augments venous return Gollwitzer Meier summarized her opinion in 1932 as follows Venous return is favored in the superior vena cava and in the hepatic veins during inspiration but decreased during expiration in the inferior vena cava and portal vessels venous return is decreased during inspiration but increased during expiration

An entirely new aspect was given to this question by the collapse theory' of Holt (1940 1941 1943) and Duomarco (1944 1945 1946 and 1950) On the basis of indirect evidence and of experiments with physical models they concluded that a decrease of intrathoracic pressure cannot influence the inflow of blood into the right atrium The argument of the adherents of the collapse theory was that with the onset of inspiration the great veins collapse at the point where they enter the chest As a consequence of this collapse resistance to flow in the collapsed extrathoracic veins must increase Therefore atrial inflow cannot become greater or may even become less during inspiration

In spite of convincing arguments in favor of the collapse theory which were

particularly advanced by Duomarco, an impressive host of indirect evidence can be marshalled in favor of an increased right atrial inflow with inspiration It was found by Wiggers (1914), Bloomfield (1945), Lauson et al (1946) and Opdyke and Brecher (1950) that right atrial and right ventricular pressures rise with inspiration This pressure rise could be explained by an increase in volume of the right heart, although admittedly it would also be explained by an increase of pulmonary vascular bed resistance (Opdyke et al 1950 Hoffman, 1951) Changes in the atrial and venous pressure pulse contours under various conditions have been attributed by Takashima (1953 a b, c, 1954) to a respirogenic *increase of venous return Increased ventricular diastolic size, recorded by differential* cardiometers (Boyd and Patras 1941) and cinematography also contribute similar presumptive evidence (Shuler et al 1942)

Summarizing

In the absence of direct evidence, various and controversial opinions as to the effect of respiration on venous return have been voiced The best represented views are the classical theory of Donders according to which venous return *increases* with inspiration and the new collapse theory of Holt and Duomarco, according to which venous return does *not* increase with inspiration

II Elementary Hemodynamics

Before dealing with the specific aspects of venous flow dynamics a brief review of a few general hemodynamic principles may be of value to those who are not in frequent contact with the subject. (For details consult Lamport [1955] Wiggers [1952])

Poiseuille's Law

Hemodynamics is a study of the forces which cause alter and regulate the flow of blood through the body In a modified form many physical laws derived from hydrodynamics are applicable to the flow of blood Generally stated the quantity of blood (Q) passing through the circulatory system or through a part of it increases with the perfusing pressure (P) and decreases with the resistance (R) to flow, as expressed by the equation $Q = P/R$ In essence this represents Poiseuille's law for nonturbulent flow through tubes it can be expressed in greater detail as

$$Q = \frac{\pi r^4(p_1 - p_2)}{8\eta l}$$

In this equation Q = the quantity of flow through a vessel (tube) per unit time $\pi = 3.1416$ r = radius of the vessel p_1 = pressure at an upstream point of the vessel p_2 = pressure at a downstream point of the vessel η = coefficient of viscosity and l = length of tube This means that volume flow is enhanced by an increase of any factor in the numerator and diminished by an increase of any factor in the denominator of the formula Each factor must be considered separately for its specific application

According to Poiseuille's law the factor which most affects volume flow is the radius of the vessel since it is raised to the fourth power in the formula As illustrated in Fig 2 volume flow through a vessel would increase sixteen times if the radius were doubled This relationship between radius and volume flow applies only to rigid tubes or vessels which have a circular cross sectional area such as arteries or full veins Thus the applicability of Poiseuille's law is best demonstrated by comparing flow through arteries of various calibers or through one artery at various stages of expansion or constriction

As is well known the regulation of blood flow in the capillary beds is achieved mainly by increasing or decreasing the diameter of the artrioles the stopcocks of the circulation We shall see in Chapter 6 that Poiseuille's law has to be modified for application to the venous system because the cross sectional area of veins is usually not circular

Blood is caused to flow from one point to another in the vascular bed by the difference of pressure between such points According to Poiseuille's law volume flow becomes greater when the pressure difference (= [pressure gradient] [$p_1 - p_2$]) increases other factors remaining the same Since p is directly proportional to flow in Poiseuille's formula flow varies linearly with

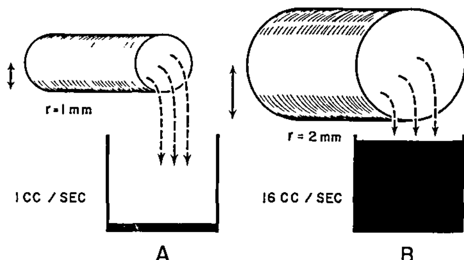


FIGURE 2 Effect of changes in radius of a vessel on flow The cross-sectional area of the vessel is circular All other factors remaining constant a vessel of 1 mm radius (A) would discharge 1 cc /sec as compared to 16 cc /sec from a vessel of 2 mm radius (B) The cross sectional area of the 2 mm vessel is four times that of the 1 mm vessel As a relation of cross sectional area to flow the expression is a fourfold increase of the circular cross sectional area results in a sixteenfold increase in volume flow

the pressure gradient This means that a doubling of the pressure gradient *along* the vascular bed will double the amount of blood passing through it For changing the amount of blood flow, nature makes less use of altering pressures than of changing the vessels radii The same sixteenfold increase in blood flow which could be brought about by doubling a vessel s radius would demand an increase of the blood pressure by sixteen times

Flow varies in inverse proportion with the length l, of a vessel Volume flow decreases by one half if the length of a vessel is doubled, other factors remaining the same Similarly the relationship between viscosity and volume flow is a simple reciprocal one Flow would decrease by one half if blood became twice as viscous

Summarizing

Volume flow through the circulatory system or part of it becomes larger with an increase in the radius of a vessel and the pressure gradient along the vascular bed Volume flow decreases with an increase in blood viscosity and the length of a vessel

TERMINOLOGY OF VASCULAR PRESSURES

What is ordinarily called blood pressure is the *lateral* pressure of blood on the wall of a vessel It is determined by the volume elasticity of the system It can exist in a closed system whether blood is stagnant or in motion Even after cessation of all blood flow (e g after cardiac arrest) the volume of blood contained in the vascular bed exerts on the walls of the vessel a pressure which comes to an equilibrium in all arteries and vein This pressure amounts to about 6 mm Hg in dogs and is called variously mean systemic pressure, ' tatic

blood pressure" or lately, "mean circulatory filling pressure" (Guyton et al 1954)

The pressure in a vessel is measured directly by inserting a cannula and connecting it to a manometer at the same hydrostatic level as the vessel If the vessel is exposed to the atmosphere the intravascular pressure is measured against the atmospheric pressure Most vessels are however, imbedded in tissues which have a certain tissue pressure that is either higher (e g , in the abdomen) or lower (e g in the thorax) than the atmospheric pressure For accuracy, the intravascular pressure should therefore, be measured against the extravascular (tissue) pressure which surrounds the vessel

Burton has introduced the term "transmural pressure" to characterize the pressure measured inside of a vessel as related to that surrounding it (Burton and Yamada, 1951) Transmural pressure is defined as the pressure difference between the intravascular and extravascular pressure This is the pressure gradient *across* the vessel s wall (inside minus outside pressure)

It should be emphasized that the transmural pressure defined as the pressure gradient *across* the wall of a vessel refers only to the lateral pressure at a given point of a vessel This must not be confused with the pressure gradient which exists *along* the vascular bed that is, between an upstream and downstream point $(p_1 - p_2)$ in Poiseuille s formula Only the latter is responsible for the *movement* of blood along the channels of the circulatory system

Recently difficulties have arisen in terminology because of the similarity in usage of the term effective pressure and transmural pressure" Originally when Henderson (1909) and Henderson and Barringer (1913) introduced the term effective pressure they used it to mean the pressure which affects the filling of the heart (effective filling pressure) In their thinking effective pressure combined both the pressure gradient *across* the vessel wall (vena caval minus intrathoracic pressure) and the pressure gradient *along* the vascular bed (pressure difference between vena caval and intraventricular diastolic pressure the difference which is responsible for the flow of blood from the caval veins into the right ventricle) Recent usage of this term does not quite coincide with Henderson s original meaning e g Seely 1948 Opdyke and Brecher 1950 Opdyke et al 1950 Duomarco et al 1950 Alexander 1951 and Coleridge and Linden 1954) As used by these authors the effective pressure has become a term for intravascular pressures in relation to extravascular pressures Used in this way the ' effective has lost its original significance and has acquired the same meaning as transmural pressure Cournand and his group circumvent terminological difficulties by calling the effective pressure net pressure In this book the term *transmural pressure* will be used preferentially because it is clearly defined and has no varying connotations

The difficulties in determining transmural pressure are mainly technical Except for very small vessels the intravascular pressure can be measured directly However the determination of extravascular pressure is quite unreliable The greatest artifacts are encountered in measuring tissue pressure in relatively solid organs (Swann et al 1950) and the least in recording the pressure which surrounds the great vessels and heart Intrathoracic pressure can be taken as the best approximation for the latter Even so calculations of transmural pres

sure in the heart cavities and large vessels hinge on the critical measurement of intrathoracic pressure in closest proximity to the place of intraluminal pressure measurement since intrathoracic pressure is not uniform in all parts of the chest (Wiggers et al, 1947) This was again emphasized and critically reviewed by Coleridge and Linden (1954)

Summarizing

For greater accuracy the intravascular pressure exerted on the wall of a vessel is not measured against atmospheric pressure, but against the tissue pressure surrounding the blood vessel The pressure gradient across the vessel wall is called transmural pressure" It is defined as the difference between the intravascular and extravascular pressure In its recent use, the term effective pressure appears to be synonymous with transmural pressure For complete analysis of a system with flowing blood one must consider the transmural pressures in addition to the pressure gradient along the flow paths

III Factors Affecting Venous Return

This chapter is confined to a brief review of those mechanisms which alter and shift the volume of blood contained in the venous system. Here, as later, it appears desirable to consider the pulmonary circuit as part of the venous system, since some factors which affect venous return to the right heart also affect return flow from the pulmonary veins to the left heart. In general, the changes brought about by shifts in blood volume are relatively slow as compared to the more dynamic effects caused by the action of the heart, respiration and skeletal muscles. The rapid dynamic changes will be taken up in later chapters.

Since the return flow of blood is an integral part of the entire circulation, it cannot be considered in an isolated manner. This holistic aspect is emphasized by the observation that the same factors (vasomotor activity, gravity, etc.) which affect venous return also influence the arterial side of the circulation. However, there is a quantitative difference insofar as one side of the circulation is more affected than the other. The difference in structure between the venous and arterial system is mainly responsible for this, the venous walls being thin and collapsible, whereas the arterial walls are thick and relatively rigid.

Effect of Gravity on Venous Return

The unique features of the circulation in the veins are to a great extent due to the wall structure which permits venous filling to fluctuate within a wide range without an appreciable change in transmural pressure. Veins are rarely fully filled and distended. Thus, the venous system can accomodate widely varying volumes of blood. This phenomenon accounts mainly for the effect which gravity has on venous return.

If veins and arteries were rigid tubes, flow in them would not be affected by a positional change. Flow through such a rigid system would only depend on the arteriovenous pressure difference at heart level, other factors remaining constant. This situation is symbolized in Figure 3A. If a rigid U tube which had been previously in a horizontal position were suddenly tilted into a vertical position, the same amount of blood would return on the "venous" side which was put into the system on the "arterial" side. However, this is not the case in a distensible system. Owing to the relatively greater filling capacity, the venous side in the body is much more affected than the arterial side by a change from the recumbent to the erect position, as illustrated in figure 3B.

In normal man the reduction of venous return under such conditions is usually of brief duration because a number of compensatory vasomotor mechanisms come quickly into play. However, it is doubtful that even with the aid of these mechanisms the same amount of blood is returned to the heart of man in the erect as in the recumbent position. If venous return and subsequently cardiac output are greatly reduced, orthostatic fainting intervenes. As is well known, the compensatory mechanisms are diminished or become inadequate after long bed rest and in a number of diseases.

Figure 3B also helps to explain the basic mechanisms by which baths have a beneficial effect upon venous return in certain circulatory disorders Immersion of the body below heart level reduces the pooling of blood in the dependent parts by increasing intravascular pressure and makes available, at least temporarily, a greater amount of blood to the heart for ejection (For discussion see Gauer 1955b)

Animals which usually do not assume an upright position have less efficient vasomotor responses than man They are almost nonexistent in the eel and snake, which can be killed by immobilization in the vertical head up posture These animals "bleed themselves to death" into their venous system (For history and details see Franklin 1937)

If in normal man the force of gravity in the head to foot direction (positive acceleration) is increased beyond a certain degree and duration, venous return becomes so greatly reduced that syncope ensues (' blackout" of pilots) This is symbolized in figure 3C In this example it is assumed that 10 times the normal gravity (10g) will distend the veins to such a degree that they accommodate a very large portion of the blood volume and that active vasomotor mechanisms are not strong enough to counteract the passive force of increased hydrostatic pressure As a result practically no blood returns to the heart The arteries in the dependent part of the body would also distend but not nearly to the same extent as the veins On the other hand if 10g act on a rigid U tube, flow through it would not be altered (Fig 3A)

Comparison of the diagrams 3A and 3C also illustrates the basic mechanism by which a pressure suit may have a beneficial effect on venous return in pilots The suit s pressure on the walls of the entire venous system below heart level counteracts the extreme distension and prevents to some degree the pooling of blood The pressure suit is meant to convert the distensible system shown in Fig

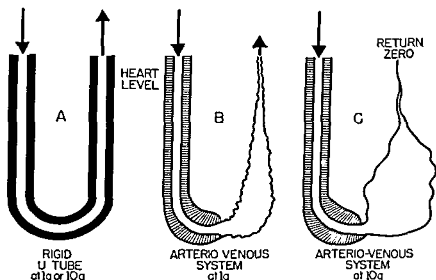


FIGURE 3 Effect of normal and increased gravity on the distensibility of the venous system Explanation in text



FIGURE 4 Influence of centrifugal force on venous return in a monkey Left Normal gravity Right 6 times normal gravity head to leg Blood contains thorotrast Both pictures taken in diastole animal sitting braced and additionally supported by a collar around the neck Centrifugal force deforms thorax and depresses diaphragm (From an X ray cinematographic film by Otto H Gauer)

3C into one which approximates more closely to the rigid system shown in Fig 3A

The effect of increased gravity on venous return is illustrated by two pictures selected from an x ray cinematographic film taken by Gauer (1944 1950) on a centrifuge (Fig 4) In the photograph on the left x ray opaque material enables one to discern the size of the normal heart and great vessels and the density of the well perfused lungs On the right side at 6g the size of the heart and great vessels is drastically reduced The lung fields are almost clear indicating that only little blood perfuses the lungs The pulmonary vascular tree is outlined below but not above heart level demonstrating that even within the pulmonary circuit the return flow of blood is greatly interfered with (For details concerning the effect of normal and increased gravity on venous return and the activity of compensatory mechanisms consult Fulton 1948 Landis 1948 Gauer 1950 1955)

Upon assuming the erect position the veins in the dependent parts increase in fullness by the force of gravity whereas veins from the upper part of the body are emptied toward the heart These upper veins collapse partially upon depleting their content and their intravascular pressure approaches zero Values less than zero are prevented from occurring by this collapse In spite of a partial collapse of the veins above and distension of those below heart level there exists a favorable pressure gradient for venous return from all peripheral regions to

the heart (Fig 5) In order to illustrate the principle of the mean flow gradient, venous pressures in the upper and lower part of the body are indicated without regard to venous valves and negative intrathoracic pressure Intravascular venous pressures are measured against atmospheric pressure

Above heart level the venous pressure is practically zero due to partial venous collapse The pressure *gradient* along the venous channels is the *height of the hydrostatic column above heart level* The gradient is great but resistance to flow in the partially collapsed veins is high (see also Chapter 6) *At* heart level

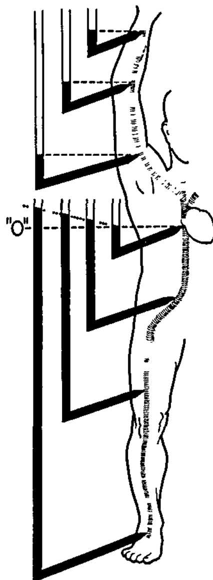


FIGURE 5 Simplified schematic diagram of venous intravascular pressures at different points above and below heart level in man illustrating the actual pressure gradients available for the return flow of blood along the venous vascular bed Description in text (Modified after figures 1 and 3 of Duomarco and Rimini 19[illegible])

(phlebostatic level) venous pressure in the right atrium is assumed to be close to zero *Below* heart level the venous pressure *gradient* responsible for blood flow from the periphery toward the heart is the *measured venous pressure minus the hydrostatic pressure column* *This* gradient is *small* as indicated in figure 5 by a dotted slope but resistance to flow in the distended veins is *very low* Flow from the lower extremities to the heart does not have to overcome a resistance of the hydrostatic pressure column as is occasionally believed The hydrostatic fluid column is the venous limb of the U shaped arteriovenous communicating tube system which as such does not hinder flow (Fig 3)

The hydraulic pressure gradients and their probable effect on venous return have been the subject of numerous studies by Duomarco and his co workers from 1944 to 1954 It should be pointed out however that the determination of pressure gradients alone without accompanying flow measurements does not provide accurate information about venous return

It must be borne in mind that the force of gravity does not accomplish work over a period of time just as static negative intrathoracic pressure due to lung elasticity is not performing work (see page 7) Only a *change* in gravity or intrathoracic pressure does work which can *alter* bloodflow

Summarizing

In an upright position gravity shifts blood into the vessels of the dependent parts of the body A larger amount is accommodated in the distensible veins than in the more rigid arteries Venous return is thereby reduced if compensatory mechanisms are inadequate Above heart level the veins are partially collapsed and the pressure gradient for flow along the venous channels is given by the height of the hydrostatic column above heart level Below heart level the veins are distended and the pressure gradient for flow along the venous bed is given by the venous pressure minus the hydrostatic column

Venous Valves

If the amount of blood available for filling the veins were not limited the presence of venous valves would not be necessary for the movement of blood from the dependent parts of the body to the heart, because veins and arteries are a communicating U shaped tube system (Figs 3 and 5) The essential function of the venous valves is to break up the high hydrostatic fluid column into small segments so that the venous reservoir is not overfilled by the full pressure of the uninterrupted column

In Fig 6A the venous pressures in two segments of a vertical leg vein are shown during the condition of muscle relaxation The pressure in each segment is the short hydrostatic column of 100 mm of water plus intravascular pressure which additionally distends the vessel wall (90 and 80 mm of water respectively) Flow from the lower to the higher segment does not occur under this condition When the lower venous segment is locally compressed e g by a muscle con traction exerting a pressure of 100 mm of water on the outside of the venous wall pressure in this segment briefly rises above that in the higher segment and flow is established (Fig 6B)

The breaking up of the hydrostatic fluid column into small segments pre

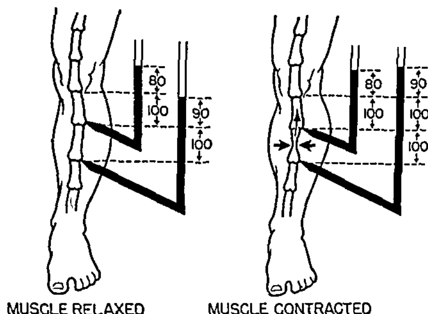


FIGURE 6. Pressures in segments of a valved vein illustrating the interrelation of hydrostatic pressure and lateral pressure at rest (muscle relaxed) and during a localized muscle contraction. Pressures in mm of water. Length of each venous segment between two valves 100 mm. Description in text.

vents the overdistension of the thin venous walls which would occur under the continuous weight of the entire fluid column.

During movements relatively small lateral pressures on the outside of the venous walls are sufficient to overcome the small hydrostatic pressure of short vertical segments of the venous blood column. When valves are incompetent a high fluid column overdistends the veins and due to a high pressure (= filtration) gradient across the venous and capillary walls orthostatic edema may ensue. (For details of valve structure and action see Franklin 1937, Burch 1950.)

Through valvular incompetance the short hydrostatic pressure columns of several segments may be joined to form a high fluid column. The continuous distension of the venous walls by a high fluid column may lead to the formation of varicose veins (see Harrison 1954, Montgomery and Zintel 1954). Despite a larger accomodation of blood in the varicose veins total venous return would not be reduced after the initial filling of these varicose reservoirs has been accomplished. The physiologically indicated treatment to counteract the continuous venous wall overdistension appears to be an intermittent reduction of the hydrostatic column (e.g. by leg elevations), an increase of extravascular counterpressure (e.g. by elastic bandages) and a surgical construction of new venous valves (Eiseman and Malette 1953).

Summarizing

Venous valves break up the high hydrostatic fluid column into small segments and prevent overdistension of the thin walled veins in the dependent parts of the body.

VENOUS DISTENSIBILITY AND TONE

As mentioned above a number of reactions come into play when a person assumes erect posture The responses by which veins and small vessels may counteract distending forces and thus prevent excessive pooling of blood have been of greatest interest to physiologists and clinicians (for reviews see Franklin 1937 Burton, 1954 Folkow 1955) Though not well documented, many of these reactions have been postulated and described previously in textbooks However only recently have animal experiments under strictly controlled conditions established conclusive evidence for the existence of specific reactions of the veins in the regulation of the circulation

When the volume of blood in a normal partially collapsed vein is suddenly augmented the intravascular pressure barely increases until the vein becomes round and reaches a certain degree of fullness The volume increase up to this point corresponds to the filling of a collapsible bag or tube without distending the walls True distension of a vein occurs only when further volume increments lead to an elevation of the intravascular pressure Contrary to common belief most excised veins are little distensible in the transverse direction though more easily stretched in longitudinal direction It appears that in the intact organism veins also have a low distensibility upon sudden volume increase (Alexander 1948b) The initial low distensibility undergoes a change however if the increased volume remains in the venous bed for a longer period Under this condition the venous walls give' slowly This phenomenon which has been called stress relaxation or delayed compliance has been demonstrated in the portal system by Alexander et al (1953) and in the pulmonary system by Sarnoff and Berglund (1952) It is attributed to the visco elastic properties of the smooth musculature in the vessel wall Whereas the low distensibility of veins may counteract sudden transient pressure increases and thereby avoid pooling of blood sustained high venous pressure may result in significant pooling due to the delayed compliance of the venous walls

An important factor which counteracts venous distension is the contraction of smooth muscles in the walls of the veins by adrenergic stimulation Since active constriction reduces the radius of the vessel the effectiveness with which the wall is capable of resisting distension is greatly enhanced (effect of Laplace) Such venoconstriction would serve to mobilize blood for return to the heart Since venoconstriction can be elicited by the same reflexes which are known to raise arterial blood pressure (pressure reflexes) the venomotor activity appears to be an important contribution to circulatory homeostasis just as are the well known adjustments of cardiac output and arteriolar resistance (Alexander 1954a b) During irreversible hemorrhagic shock the venomotor mechanism fails this leads to a marked pooling of blood in the venous system (Alexander 1955)

Summarizing

Veins have a relatively low distensibility upon transient increases in intravascular pressure Their smooth muscles contract actively upon adrenergic and reflex stimulation and contribute considerably to circulatory adjustments Pooling of blood in the splanchnic venous system occurs due to passive yielding of

the venous walls upon prolonged action of intravascular pressures, physiological reflex venodilation and failure of the venomotor mechanism in irreversible hemorrhagic shock.

NERVOUS AND HUMORAL REGULATION

Undoubtedly the specific reflex venomotor activity of the splanchnic bed discussed above is a factor of fundamental importance in the nervous regulation of venous return. Apparently the same adrenergic reflexes which evoke splanchnic venoconstriction bring about arteriolar constriction in the entire organism and by a simultaneous generalized venoconstriction cause a transient increase in total systemic venous return (Rashkind et al. 1953). On the other hand, cholinergic reflexes which lead to arteriolar dilatation also dilate the veins and result in a temporary decrease of total venous return by blood pooling in the venous channels.

The profound effect of adrenergic and cholinergic stimulation upon the volume elasticity characteristics of the venous system is graphically illustrated in Fig. 7. These characteristics have been assessed by Peterson (1951, 1952) through rapid short duration fluid injections into the abdominal inferior caval tree of dogs. The modulus of distensibility of the veins is plotted on the ordinate against the intravenous pressure (abscissa).

Curve A shows that under normal conditions the veins are not completely filled. The sharp break in the curve at a pressure of 100 mm. of water indicates the point at which the vessels become round. Then, up to about 270 mm. water the curve remains flat, indicating that $\Delta P/\Delta V$ is constant. Above this pressure the curve rises and becomes nonlinear presumably because of the distensibility characteristic of muscle and collagenous tissues in the venous walls. Curve B indicates that cholinergic stimulation leads to a marked venodilatation (break in curve at 180 mm. water) which would permit considerable pooling. Following the injection of epinephrine the veins become round at a pressure of 40 mm. water. This fact and the steep slope of the curve indicates that the veins are more rigid and contracted during adrenergic stimulation (Peterson 1956).

The entire venous bed may therefore be looked upon as a variable blood depot. Blood in this type of a depot is, however, not withdrawn from the active circulation. It merely *circulates slowly* when the venous channels are widened by prevailing parasympathetic tonus. Since the central veins constitute a considerable part of this "depot," blood is readily available for a sudden increase in right heart inflow and subsequent output as demand arises. A corresponding condition prevails for the left side of the heart as pointed out by Sjostrand (1953). Here the pulmonary vascular bed represents a readily available large reservoir which permits a sudden increase of left heart filling and output. This would serve specifically for the rapid adaptation of the circulation to positional changes and physical work. The dynamic mechanisms by which the action of the heart can contribute to its filling from the reservoirs will be taken up in chapter 9.

The importance of the large pulmonary blood depot which is immediately available to the left heart and systemic arteries should be emphasized. According to Sjöstrand (1953) about 30 per cent of the circulating blood volume is con

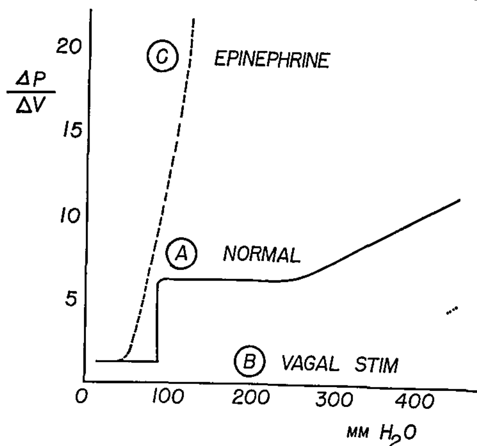


FIGURE 7 Volume distensibility characteristics of the venous system under (A) normal conditions during (B) cholinergic and (C) adrenergic stimulation Ordinate $\Delta P/\Delta V$ in mm H_2O/Ml volume change Abscissa mm water pressure measured in the inferior vena cava distal to the renal veins The values are limited to pressures occurring within the physiological range in the venous system (Modified from unpublished data after Lysle Peterson)

tained in the thorax of the normal human in the recumbent position Three fourths of this amount is in the pulmonary vessels and one fourth in the heart during diastole The volume of reserve blood in lungs and heart is larger when vagotonus prevails and smaller when sympatheticotonus prevails

Trained athletes have a greater blood volume than average persons and their thoracic blood reservoir is accordingly larger Since this reservoir is proportionally distributed between lungs and heart their residual ventricular volume at rest is larger than that of average subjects (Reindell et al 1953 Gauer 1955a)

Upon sudden demand by physical exercise the large residual ventricular volume and pulmonary blood reservoir are *first* called upon to pay for the deficit between the temporarily lagging systemic venous return and the immediately increased left ventricular output This period of dynamic imbalance lasts only a few seconds until increased return from the systemic veins due to reflex venomotor action (Page et al 1954) occurs and as a consequence of increased

left heart output restores the equilibrium at a higher level of flow A correspond ing situation prevails when a person rises from the recumbent position As men tioned before return from the systemic veins is then briefly reduced (Fig 3B) In normal man approximately 600 cc of blood suddenly sags into the vessels of the dependent parts This amount is immediately compensated for primarily from the intrathoracic blood depot It is important that a large intrathoracic reservoir is available for left heart venous return to prevent a temporary re duction of left heart output which may lead to a drop in arterial blood pressure and subsequent orthostatic fainting Trained athletes have in these re pects better than normal compensatory abilities owing to their relatively larger tho racic blood depot

If the intrathoracic blood reservoir is diminished from 30 per cent to less than 15 per cent of the total blood volume then this reservoir becomes inadequate and left heart output decreases temporarily upon postural changes Under these circumstances the left heart cardiac output depends directly upon the fluctua tions of the return flow from the systemic veins (Sjostrand 1953) Anesthesia surgical trauma and open thoracotomy shift the blood in the organism in such direction that less than 15 per cent of the total blood volume is contained in the thorax This explains why aside from other factors under these conditions the latitude of circulatory regulations is greatly diminished It explains also how in experiments on anesthetized animals the importance of the thoracic blood reservoir for certain sudden circulatory adjustments has not been fully appre ciated This has also been pointed out by Rushmer (1954, 1955a) Apparently the basic relations of venous return and cardiac output as represented by Star ling s law can be overshadowed under normal physiological conditions by the mechanisms outlined above but they come into play when the circulatory reserve is diminished and under pathological conditions The well known *blood depots in spleen and other organs seem to have the role of auxiliary depots* which are called upon if the readily available blood reservoirs in the lungs and systemic veins (and possibly also portal veins) are insufficient to meet the de mands (For reviews on blood depots pressor reflexes and humoral control con sult Wiggers 1950 Fulton 1955 Houssay 1955 Rodbard and Katz 1955)

The regulation of venous return and blood volume distribution is aided by a number of reflexes which are elicited from stretch receptors in the venous walls though difficulties have been encountered in establishing clear cut evidence for the existence of some of these reflexes (reviewed by Aviado and Schmidt 1955) Distension of the caval veins and right atrium reduces reflexly the tone of the vagus nerve and accelerates the heart (Bainbridge reflex) A similar reflex is elic ited by pulmonary venous dilation (Takino 1951) Rise of pressure in the ab dominal caval system initiates a veno venous reflex by which the sympathetic *tone of the intestinal veins is reduced (Alexander 1956) In addition to these* circulatory dynamic effects the stimulation of stretch receptors in the area of the great veins heart and pulmonary vessels enhances urine flow These receptors appear to play an important role in the control of plasma volume and central venous pressure (Gauer et al 1954 Henry Gauer and Reeve 1956 Henry Gauer and Sieker 1956 Gauer et al 1956)

Local distension of the walls in peripheral veins results in constriction of the

arterioles supplying the particular venous bed The throttling of arteriolar in flow diminishes in turn the venous engorgement (negative feedback) The precise nature of this veni vasomotor reflex remains to be elucidated espe cially whether or not it is a true reflex axon reflex or other mechanism (Yamada and Burton 1954 Haddy and Gilbert 1956)

Summarizing

The entire venous system becomes dilated but less distensible upon choliner gic stimulation whereas it is constricted but elastically more distensible under adrenergic influence Central systemic veins and the pulmonary vascular bed represent variable blood depots which are readily available for increase in heart inflow and output upon sudden demand In normal recumbent man the large blood reservoir in lung and heart is immediately utilized during sudden physical work or positional change to increase left stroke volume before systemic venous return can be increased appreciably When the thoracic blood reservoir is reduced in anesthesia or by trauma the output of the left heart depends directly upon fluctuations of systemic venous return Reflexes from stretch receptors in the venous walls may aid in regulating heart output the total circulatory fluid vol ume and arterial inflow into local venous beds

IV Present Problems of Venous Return Dynamics

From the historical review in the first chapter it is evident that our knowledge of the forces which determine the return flow of blood needs further expansion. The present basic problems concerning the dynamic aspects of venous return can be crystallized around the following three main topics: (1) The effect of venous collapse on pressure and flow in the veins (venous hemodynamics); (2) The effect of respiration on venous return; and (3) The effect of the heart's action on venous return.

Venous Collapse Phenomena

The concept of Holt (1940, 1941, 1943), that venous collapse can reduce blood flow through a vein despite an increase in the pressure gradient along the vessel, has stimulated the investigation of hemodynamics in the venous system. It is well known that in the high pressure system of the arteries volume flow through a vessel increases with an increase of the pressure gradient between an upstream and downstream point of the vessel if arteriolar resistance remains unchanged. Therefore pressure measurements at different points along an artery permit a fair estimate of quantitative changes in volume flow.

This situation prevails because arteries with semi-rigid, elastically distensible walls behave essentially like uniformly patent tubes. This is not necessarily so on the venous side. In a low pressure system with collapsible tubes the pressure gradient between two points may not give information about the volume of blood flow between the points. For example, pressure at a distal point of a vein may be 50 mm water and at a proximal point 10 mm water, but volume flow through the vessel may be practically nonexistent because between the two points a segment of the vessel may be partially collapsed, causing a high resistance. Therefore, in this case measurements of venous pressures cannot give information about changes of blood flow through the veins.

A well known example from the student laboratory illustrates this situation. Venous pressure falls slightly in normal inspiration when it is measured directly with the Moritz and Tabora method in the forearm. During inspiration the pressure gradient between the forearm and right atrium increases and one might conclude that an increased amount of blood flows from the forearm to the heart. During deep inspiration venous pressure in the forearm *rises* slightly. The pressure difference between forearm and right atrium has become considerably greater with deeper inspiration. Nevertheless, as we shall discuss in detail, volume flow does not necessarily increase.

The present problem is therefore to study in the venous system the pressure-flow relation which are to a great extent determined by the collapsibility of the vein.

Controversial Effect of Respiration

Closely linked with the first topic is the intriguing controversy as to whether or not venous return is aided by respiration As already mentioned there are two diametrically opposed schools of thought One represented by the classical theory of Donders is based on the assumption that veins behave like arteries as uniformly patent tubes Flow in them would increase directly with an increase of the pressure gradient If for example the pressure gradient between the jugular vein and the right atrium is increased by inspection inflow into the right heart would be augmented The other view the collapse theory states that except for abnormal and pathological conditions the negative pressure in the thorax and its variations are incapable of influencing venous return directly " (Duomarco Recarte and Pimini 1944)

A reinterpretation of the known data could never reconcile the two conflicting views It has been necessary to develop new experimental approaches to resolve the problem

The Heart as a Factor in Venous Return

The last problem which still calls for elucidation after centuries of controversy is the question Does the heart by its own action draw blood toward it or not? Is it a suction pressure pump or is it a pressure pump only?

This problem presents two facets First what is the effect of ventricular systole on venous return and second what effect has ventricular diastole on venous return?

Bohme (1936) believed that he had solved the first problem by the use of x ray–opaque material in the veins His observations are adequate evidence that the ventricular contraction can accelerate blood flow in the thoracic caval veins However this acceleration of the blood column does not mean that right atrial inflow is *quantitatively* increased during systole by myocardial contraction Bohme's findings are purely of qualitative nature as pointed out by Holzlohner and Schonerstedt (1940) Bohme himself stated repeatedly that during the period of systolic acceleration of blood flow both caval veins narrowed This indicates that the *amount* of blood passing quickly through the veins during ventricular systole could have been equal to or even less than that flowing during diastole Actually in a vein one cannot predict from an acceleration of flow whether more or less blood passes through the vessel because the cross sectional area of a vein varies remarkably For example The shape of the central veins could be nearly circular during ventricular diastole and a large volume of blood might flow slowly through the wide open vessels into the heart On the other hand the veins may become elliptic due to the partial collapse during ventricular systole and only a small volume of blood might pass through the narrowed vessel into the right atrium though it would flow at a high rate The present techniques of x ray cinematography cannot provide a quantitative resolution of this problem

Another difficulty of Bohme's method should be pointed out He could only observe an acceleration of the blood column during systole and a deceleration during diastole but details of the time course of the events could not be es

tablished by him Holzlohner and Schonerstedt (1940) found that volume flow in the external jugular vein of the dog during ventricular systole was not nearly so great as anticipated or suggested by Bohme's qualitative observations However Holzlohner's data do not resolve the problem either because he undertook the flow measurements in a peripheral vein where arterial impacts and various unanalyzed artifacts apparently distorted his curves He could not correlate accurately the flow changes with the cardiac cycle and did not record pressures simultaneously

A new quantitative approach is therefore necessary to study the force which the ventricular myocardiac contraction may exert on venous return

The second facet of the questionable suction pressure pump action of the heart deals with the effect of ventricular diastole on venous return At present, there is no conclusive experimental evidence available to invalidate the dictum of Wiggers and Straub which states that diastolic ventricular inflow must be *passive since no negative pressure has been recorded reliably in the ventricular* cavity during diastole (For a discussion of the energy available for rapid diastolic filling see also Rushmer et al 1953)

Thus it is up to the proponents of the opposite view (Guasp 1954 Cignolini 1954 Villa 1954) to furnish indisputable experimental evidence that blood is actively sucked into the ventricle at the beginning of diastole (see also foot note page 110)

These basic problems are interwoven with the broader aspects of venous return which relate it to homeostatic mechanisms (Landis 1950) and to the rest of the circulation in health and disease Green (1948) summarized the integration of the different problems and the difficulty of resolving them by the use of pressure measurements as follows Recent interest has been focused on the mechanisms controlling venous return both under physiologic conditions and in disturbances of homeostasis such as are seen in shock and heart failure Attempts in this direction have been made by recording simultaneously the right atrial pressure cardiac output and aortic pressure However, interpretations of these data are complicated by fluctuations of central venous pressure produced by respiration by the fact that extremely large variations in the quantity of blood in the central veins and atria may occur with little change in level of the recorded pressure and finally by the fact that cardiac output may vary independently of the central venous reservoir pressure and therefore result in change of atrial pressure in a direction opposite that expected to result from the simultaneously occurring variation in venous return Fluctuations in capacity of the central venous reservoir and atrium may also cause a change in level of pressure in these structures in the absence of any alteration in cardiac output or venous return thus further complicating interpretation "

From the foregoing it is evident that descriptive observation and circumstantial evidence from pressure measurements which lend itself to various interpretation cannot penetrate to the core of the problem In this field as in many others in modern biological sciences the older techniques of a descriptive and observing approach must be replaced or at least supplemented by quantitative methods

In recent years the most fruitful approach has consisted of *measuring blood*

flow directly and *quantitatively* in the venous system and correlating it with the simultaneously recorded pressures in the vessels

In order to gain quantitative information of hemodynamic events it is always necessary to measure two parameters e g flow and pressure gradient along the vascular bed for determining the third resistance ($Q = P/R$ Chapter 2) Measurements of pressure alone can furnish only indicative evidence Technically it is much easier to measure pressure than flow Jarisch realized this dilemma as early as 1928 when he stated for the development of circulation research it has certainly been a disaster that it is relatively cumbersome to determine volume flow but so easy to measure the blood pressure For this reason the blood pressure manometer has gained a rather fascinating influence though most organs do not need pressure but volume flow Although Jarisch had primarily arterial flow in mind his statement is even more applicable to the venous system For technical reasons measurements of blood flow in the low pressure system of veins is much more difficult than in the high pressure system of the arteries Great efforts have therefore been made in recent years to develop venous blood flow recorders Since much of the success in approaching present and future problems depends upon proper instrumentation the next chapter is devoted to a detailed survey of techniques of blood flow recording

Summarizing

Three basic problems of venous return take the center of scientific interest at present These are (1) the effect of venous collapse on pressure flow relations and venous hemodynamics (2) the influence of respiration on venous return and (3) the attraction of blood in the veins by the heart s own action during systole and/or diastole An elucidation of these problems depends a great deal upon direct and quantitative measurement of venous blood flow

V Methods for Venous Flow Measurement

In the search for the ideal flowmeter scientists have developed instruments which make use of almost every conceivable physical principle Each instrument has only a limited application, and numerous disadvantages There is no universal flowmeter which is preferable to all others The choice of the proper flowmeter depends upon the nature of the problem in whose solution it is to be employed Generally speaking the simplest and most direct method is the best Considerations here are restricted to the specific aspects of venous flow apparatus and their recent development For an account of flowmeters in general the reader is referred to the excellent articles of Green (1948) and the new (eighth) volume of Methods in Medical Research

For an understanding of many flow tracings shown in this book, the difference between two types of continuous flow recording should be mentioned The two types are cumulative recording and rate recording

1 Cumulative (also called slope or integrated) recording is most advantageously used to measure venous drainage, though it can also be used for flowmeters inserted into a vessel Flow is recorded as a slope (Figs 24 and 28) The higher the flow rate the steeper the slope A constant flow rate produces a straight sloping line (Fig 24B) A change in flow rate produces a change in the angle of the slope Before flow begins and again after it ends the tracing forms a horizontal line but the two are at different levels Volume is measured by the difference in level i e the height of the tracing The advantage of cumulative flow recording is that the total volume during a given time interval may be measured directly on the record It is not necessary to integrate different rates of rapidly changing flow in order to obtain total flow

2 Rate (also called velocity) recording is more frequently used to measure uninterrupted flow through a vessel The flow rate is recorded as an elevation of the tracing above the zero line (Fig 30) A constant flow rate produces a horizontal line Increase in flow rate leads to an upstroke decrease to a downstroke of the curve In the absence of flow (zero flow) the tracing returns to the zero line The volume is calculated by measuring the area under the flow curve

Two types of direct flowmeters have been successfully employed for a study of venous flow dynamic They are (1) Venous drainage flowmeters and (2) Pulsatile flowmeters

Venous Drainage Recorders

This method is the simplest Outflow from a cannulated vein is collected and continually registered Most devices used for this purpose are cumbersome and have such great inertia or friction that they cannot faithfully follow rapid flow changes (Brubach 1947 Ligon 1947 Lindgren and Uvnas 1954) The best instruments are the strain gauge flowmeter of Alexander (1948b) the tambour

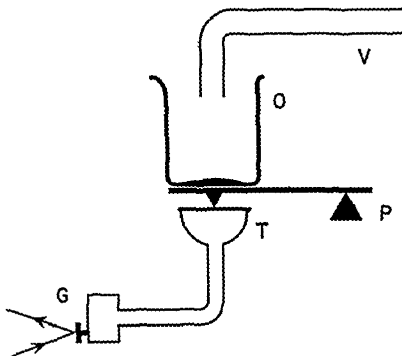


FIGURE 8 Schematic diagram of an optically recording Tambour flowmeter Description in text

flowmeter (Brecher and Ritter 1951) and the mechanical balance of Zieske et al (1955) The first mentioned has the advantage of greatest flexibility and *easily adjustable sensitivity*

As the tambour flowmeter was used for several studies reported here it is described briefly (Fig 8) Blood from the cannula V drains into a receiver O *Its weight presses on a tambour T which transmits the pressure to an optical* manometer G by a liquid system A light beam deflected by the mirror on the manometer makes a sloped tracing on a photokymograph The natural frequency *of a flowmeter system of 20 cycles/sec permits tracing of sudden flow rate changes with a minimal time lag The calibration reveals a linear response of* the instrument

Summarizing

Venous drainage recorders of adequate frequency response can be suitable for measurement of moderately fast changes of venous flow They are not adequate for recording variations over single cardiac cycles

Recording of Pulsatile Flow

For better understanding of pulsatile flowmeters brief mention should be made of mean flow recorders some of which have also been employed in the venous system Mean recorders can only register the mean or average rate of flow Causes for the inability to follow quick changes of flow include mechanical

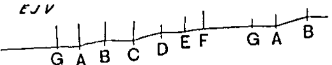
inertia damping friction the length of time necessary for observing the movement of the blood, the slow frequency response of electrical amplifiers or a combination of any of these factors Attempts have been made to record pulsatile changes in veins and arteries with mean flow recorders The cumulative curve which Burton Opitz (1902) traced with a modified Hurthle Stromuhr in the external jugular vein of a dog may serve as an example (Fig 9, left side) The middle record of the three shows by the steeper slope (A B and C D) an increase in blood velocity These curves have often been reproduced in text books as evidence that venous blood is 'sucked' into the right atrium during ventricular systole (A B) However it should be pointed out that this evidence is of a qualitative nature only The Stromuhr (Fig 9 right side) has too much inertia to permit a faithful reproduction of flow events The moving parts overshoot greatly once they are set into motion Straub (1923) and Holzlohner and Schoenerstedt (1940) called particular attention to this fact The estimate of Bohme (1936) that ten times as much blood flows toward the heart during ventricular systole than during diastole was mainly based on the quantitatively incorrect figures of Burton Opitz (1902)

It must be realized that the same physical criteria which Otto Frank demanded for accurate manometry also apply to phasic flow recording In order to obtain a faithful reproduction of rapid flow changes the recording instrument must have a high natural frequency response just like a manometer However it is easier to meet this standard with a manometer than with a flowmeter and easier with flowmeters used in the arterial system than with those used in the venous system

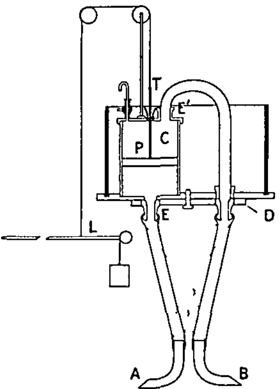
In arteries it does not matter much if a flowmeter introduces a moderate resistance to flow because the pressure in this system is high and some pressure loss can be tolerated For example a pressure drop of 5 mm Hg across a flowmeter will not interfere greatly with the circulation if the pressure head available is thereby reduced from 120 to 115 mm Hg On the other hand an equivalent resistance introduced into a vein would lead to congestion distal to the flowmeter because venous and capillary walls yield more than arterial walls When Smith and his co workers (1952) inserted a rotameter into the central venous circulation of dogs this resulted in a rapid circulatory collapse since the animals were unable to raise venous pressure to and maintain it at a level high enough to overcome the resistance offered by the rotameter

The problem of an unduly great resistance introduced by a flowmeter particularly concerns the use of the differential pressure flowmeters These instruments have a high natural frequency response which makes them suitable for phasic flow recording However in order to obtain adequate sensitivity appreciable resistance must be introduced into the vessel The problem of design in a differential pressure flowmeter is to find a compromise among resistance sensitivity and frequency response

For quantitative measurement of flow by meters that record velocity and direction it is indispensible to know at each moment the cross sectional area of the vessel through which the fluid volume passes As pointed out previously in the discussion of the x ray observations of Bohme a velocity increase of the fluid column does not necessarily mean that the volume of fluid is increasing







The cardiac variations

FIGURE 9 Flow tracing obtained from the external jugular vein (EJV) with a modified Hürthle Stromuhr (right) by Burton Opitz in 190 They illustrate how artifacts created by the inertia of a low frequency recording system can distort flow curve Symbols of tracings to the left (approximately related to cardiac cycle) G = beginning of atrial systole A = peak of atrial systole B = early ventricular ejection C = end of ventricular ejection D = rapid ventricular inflow phase E = slow ventricular inflow phase F = diastasis Symbols of Stromuhr to the right A and B = cannulae in jugular vein C = cylinder filling with blood entering at E and leaving at E' P = plunger moved by blood T = transmission to lever L D = plate which permits rotation of Stromuhr for filling the cylinder in reverse direction after plunger has moved up Cannulae connections after turning of D are indicated by dotted lines

proportionally Unrecorded fluctuations in the diameter of the vessel preclude any measurement of *volume flow* This factor is of greater importance in veins than in arteries since the cross sectional area of veins usually undergoes greater fluctuations than that of the arteries Momentary area changes in veins are caused by collapse whereas in arteries they are caused primarily by elastic expansion

Two procedures appear most fruitful in establishing quantitatively reliable conditions for flow measurements in veins These are (1) continuous recording of the normal fluctuations of the cross sectional area or (2) fixing the cross sectional area of the vessel at the point of flow measurement The latter may be accomplished by inserting a ringlike structure (Fig 15) or by expanding the vessel from the inside or outside by mechanical means (Fig 17) In arteries this problem is easier to solve because their expansion can be prevented by applying a ring or sleeve around the vessel as commonly done in the use of electromagnetic flowmeters

Distortion of the flow pattern may also arise from the use of overly long tubing to conduct blood to and from the flowmeter Long tubing may delay the flow pulse though this effect will be of little importance if the tubing is rigid and not excessively long Further the fluid column in a rigid tube may through its inertia cause an overshoot of the column upon rapid acceleration or deceleration This can be corrected by judicious damping e g , with a screw clamp However since damping increases the resistance to flow, this procedure can only be used in the high pressure system of the arteries

If the wall friction of the tubing is too high the full extent of the flow accelerations and decelerations can not be recorded The effect would be the same as overdamping A rigid tube leading to and from a flowmeter actually becomes an integral part of the meter and thus influences its natural mechanical frequency response Obviously it always lowers it A high fidelity flowmeter when inserted into long rigid tubing used for the cannulation of a vein is converted into a low frequency instrument unsuitable for faithful recording of the flow pattern

Summarizing

Quantitatively accurate measurement of rapid flow changes in veins is difficult due *to the following facts (1) The high flow accelerations require in*struments with a high natural frequency response (2) The small pressure head available in veins exclude or limits the use of flowmeters with an inherently large resistance (3) The collapsibility of veins necessitates the establishment of a reproducible or known cross sectional area of the vessel (4) The use of tubing conducting blood to and from a flowmeter is limited because it may distort the flow pattern by reducing the assembly s frequency response

Differential Pressure Flowmeters

If a pressure difference is created by introducing a fixed device between two points in a streaming fluid this difference will vary in proportion to the velocity of the fluid The pressure difference can be created in various ways as illustrated in Fig 10

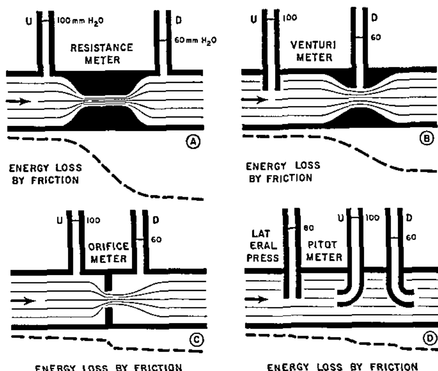


FIGURE 10 Schematic diagrams illustrating the creation of pressure differences in streaming fluid for measuring velocity of flow by differential pressure manometry U = upstream manometer D = downstream manometer Difference of hydrostatic pressure in side tube manometer is symbolized by the fluid level in mm of water Energy loss by friction is plotted as a broken line below each type of differential meter Description in text

(a) *Resistance flowmeter* Narrowing the lumen causes friction thus potential energy is lost The lateral pressure on the wall above the area of constriction is higher than below the narrowed part (Fig 10A) Application of this principle alone is not practicable in the venous system because of the high resistance necessary to produce a sufficient pressure drop Each of the three other devices (B C D) shown in Fig 10 also offers some resistance and the pressure difference created by them is due to the fact that they act partly as resistance flowmeters

(b) *Venturimeter* Essentially a venturimeter is a wide tube which has a short constricted segment (Fig 10B) In the wide part velocity is low thus the potential energy which creates the lateral pressure on the wall is great and the kinetic energy (energy of flow) is small In the narrowed segment blood flows faster and potential energy is converted into kinetic energy The downstream manometer tube at the constricted area registers a lower lateral pressure than the upstream tube Beyond the constricted area kinetic energy is reconverted into potential energy The energy loss owing to friction is small This very reliable method had been widely used in technical applications but was not employed by physiologists until de Burgh Daly (1926) Wagoner and Livingston (1928) and Lauber (1928) used it for measurement of blood flow

In our laboratory we successfully used a large bore venturimeter of our own design (Fig 39) for measuring pulsatile changes in inflow into the central veins (Brecher et al, 1952) This instrument combines adequate sensitivity with low resistance and absence of turbulence up to flow rates of 720 ml/min Its frequency response is approximately 40 cycles/sec According to Green (1948) a Venturimeter does not register flow reversal However, the instrument we used recorded reversed flow

(c) *Orifice meter* When a tube is narrowed at a point (orifice), the streamlines continue to converge beyond the orifice (Fig 10C) Lateral pressure is maximally reduced downstream from the orifice at a distance corresponding to half of the tube's internal diameter Therefore the downstream manometer is connected to the flowmeter at this point Interchangable plates of different orifice sizes (Gregg and Green 1940) or a variable screw which narrows the lumen (Shipley et al 1943) permit adjustment of the sensitivity The orifice meter has been widely employed for studying the phasic flow pattern in arteries (Reissinger 1928 Gregg and Green 1940 Shipley et al, 1943 Kantrowitz and Kantrowitz 1953 and others) We were unsuccessful in using Gregg's or Shipley's original devices or modifications thereof in veins The sensitivity was inadequate when large orifices of low resistance were used while small orifices introduced too much resistance Furthermore the range of flow rates free from turbulence was very narrow

(d) *Pitotmeter* When a Pitot tube with its open end directed upstream is inserted into moving fluid the energy of movement is added to the existing potential energy (pressure on the wall) and a higher net pressure is recorded in the Pitot tube When the opening of a Pitot tube faces downstream the kinetic energy of movement is deducted from the potential energy (pressure) The Pitot effect results in a difference between the hydrostatic fluid levels of the upstream and downstream Pitot tubes This is symbolized in Fig 10D Here the potential energy of the fluid reservoir (to the left of the drawing but not shown) corresponds to a column of 100 mm of water In the tube of flowing liquid potential energy (wall pressure) amounts to only 80 mm lateral pressure (as indicated by the straight manometer to the left) When the kinetic energy of flow is reconverted into potential energy it results in a column of 100 mm of water (80 + 20) in the upstream Pitot tube (which faces the current) and of 60 mm of water (80 − 20) in the downstream Pitot tube In this example the energy loss by friction is neglected Compared with other differential flowmeter Pitotmeters produce less resistance—and thus less energy loss by friction—for any given pressure difference created For this reason they appear best adaptable to venous flow measurements The detailed study of Pitot meters by Alois Muller (1954a) encourage their use in future experimentation

The first Pitotmeter for blood flow was constructed by Cybulski in 1885 modified by Kh..ecki in 1925 and finally applied by Fleck in 1934 for venous flow registration The e authors projected the menisci of the upstream and downstream Pitot tubes separately on a photokymograph Their flow cannula was bulky and the inertia of the unit made it unreliable for phasic recording other than slow change of venous flow associated with respiration

In Fig 11 two Pitotmeters are shown which have been successfully employed

in studying phasic changes of flow in the central veins They are used in conjunction with a differential manometer (see also Fig 12) in order to produce a more satisfactory frequency response than Cybulski and Flick obtained The device shown in Fig 11A was developed by Eckstein, et al (1947) to measure inferior vena caval flow in an open chest normal dog and in hemorrhagic shock Adequate sensitivity could only be obtained by providing the small baffle plate

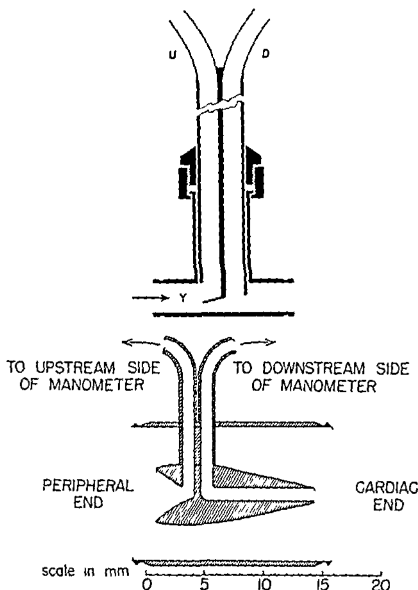


FIGURE 11 Schematic diagrams of two types of Pitotmeters used for measuring flow in the venae cavae Top flowmeter employing a baffle (Y) for increasing the pressure difference (redrawn from Eckstein Wiggers and Graham 1947) Bottom torpedo shaped flowmeter with good streamlining characteristics (Mixter 1953)

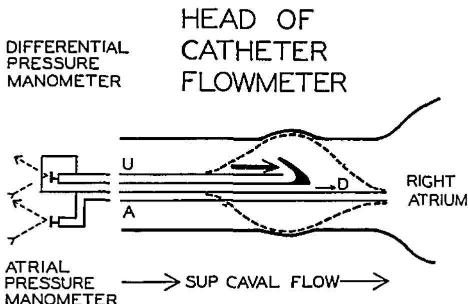


FIGURE 12 Schematic diagram of Pitot type catheter flowmeter and its manometer connections The flowmeter head is shown resting in the superior vena cava the walls of which are expanded from the inside by a basket Description in text

I on the upstream Pitot tube This renders the instrument insensitive to flow *in the reverse direction (backflow) The natural frequency response is ap*proximately 45 cycles/sec

Since Eckstein s instrument is bulky and does not permit chest closure our laboratory developed the small Pitotmeter shown in Fig 11B (Mixter, 1953 Brecher and Mixter 1953) It has a streamlined body in the center of the flow cannula to reduce turbulence The upstream pressure pickup is funnel shaped the downstream pressure pickup forms the narrow tail of a torpedo like body This device permits recording of forward and reverse flow without turbulence over a range of flow rates from −1200 to +1800 ml /min when used in dimen ions fitted for the caval veins The resistance is small and no bulging of the cava on the upstream side of the flowmeter was observed Unfortunately the natural frequency response of this instrument with the tubing leading to the differential pressure manometer ranges only from 8 to 35 cycles/sec This suffices for recording re pirogenic flow changes but is too slow for faithful recording of the fast variations of flow that occur during the cardiac cycle

In Fig 12 a Pitotmeter is shown which can be introduced as a rigid catheter into the large intrathoracic cavae without severing the ve sel or opening the che t (Brecher 1953) The catheter flowmeter consists of three tubes labeled A *U* and *D* The end of tube A lies in the right atrium and transmits the atrial pul es to an optical manometer depicted in the lower left section of Fig 12 The end of tube *U* faces up tream whereas tube *D* is directed downstream The pres ure difference activates a differential manometer (upper *left Fig 12) The* catheter head is held in midstream by five stainle s steel prings which can be expanded by turning a screw at the catheter handle after the catheter s inser

tion Use of the catheter flowmeter reduces the necessary operative procedure to jugular venesection only Volume flow can be quantitated owing to the fixation of the vessel s cross sectional area by the basket expansion Because of the long catheter tubing the natural frequency response ranges only from 15 to 35 cycles/sec This instrument has been used successfully for studying respirogenic changes of venous return

A limiting factor of all differential pressure flowmeters described above is the optically recording differential pressure manometer This device was first designed by Otto Frank in 1899 modified by Fleisch in 1920 and later improved by Gregg and Green (1940) Even in its latest form it is cumbersome to work with and it reduces the frequency response of the assembled apparatus because of the liquid column in the tubing leading from the flowmeter to the manometer

The schematic diagram in the upper left part of Fig 12 illustrates the principle of the differential pressure manometer The high upstream pressure *U* symbolized by a heavy arrow is transmitted to the inner saline filled chamber of the manometer The lower downstream pressure *D* symbolized by a small arrow is conducted to the outer saline filled chamber of the manometer These pressures act from opposite sides on a thin rubber membrane which is hence deformed by the pressure difference The membrane excursions are recorded from a small mirror on the membrane Light reaches and leaves the mirror through a glass window in the outer chamber

Summarizing

Differential pressure flowmeters using the Pitot principle appear more suitable for venous flow measurement than those based on the resistance Venturi or orifice principles

RECENT DEVELOPMENTS

Attempts have been made recently to improve the fidelity of differential pressure flowmeters by using electrically operating manometers This helps by reducing the length of the fluid columns Muller Laszt and Pircher (1948) describe a differential manometer with electrical transmission suitable for flow recording Baxter and Pearse (1951) developed a rather complicated condenser differential manometer for measuring flow in the pulmonary artery with a Pitot meter It could be adapted for venous flow recording

Nilsson and Kramer (1954) constructed a Venturimeter which they inserted into the inferior vena cava (Fig 13) The pressure difference is created by decreasing the internal lumen of the flowmeter tube (a) by ⅓ This introduces some resistance to flow and creates minimal turbulence The pressure difference (electrical signal) is however small and requires great amplification Pressures are conducted through fairly short upstream and downstream manometer tubes to a differential manometer utilizing the strain gauge principle The frequency response of the entire assembly is limited to 30 cycles/sec at the amplifier s output circuit by a very sensitive and hence slowly responding galvanometer This however could be improved upon in the future

The differential conductance manometer of Pappenheimer (1954) could be

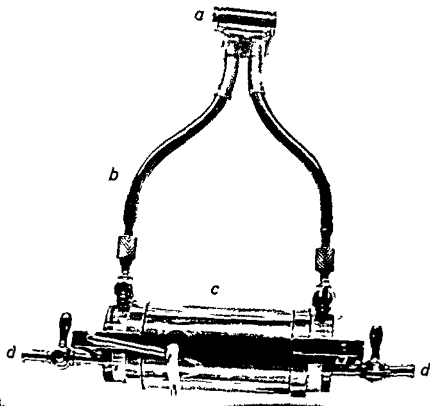


FIGURE 13. Venturimeter and strain gauge differential pressure manometer for measurement of volume pulses in central veins. a = Venturimeter; b = rigid upstream and downstream manometer tubes connecting Venturimeter to differential manometer; c = strain gauge differential manometer; d = stopcocks for flushing and checking of zero flow. (After Nilsson and Kramer 1954.)

applied to recording of phasic flow in veins when used in conjunction with suitable pressure pickup devices. Its natural frequency is high. From a hemodynamic viewpoint the best constructed Pitotmeter is the electrical differential manometer of Betticher, Maillard and Muller (1954), which has an excellent frequency response and great sensitivity.

Summarizing

Replacement of the optical differential manometer by electrical pickups can improve the fidelity of differential flowmeters.

Critique of Differential Pressure Flowmeters

Differential pressure flowmeters have a nonlinear calibration. The flow signal reflects the square of the flow velocity. This makes the computation of volume by integration of the flow tracings laborious and limits their use for timing flow curves with a zero phase. (For various suggestions see Green 1948, Mixter 1953, Kantrowitz and Kantrowitz 1953.)

Differential flowmeters confront their designers with the same dilemma facing engineers in high fidelity recording of small rapid pressure fluctuations If the physical force (signal) is small the gain of the recording instrument must be greatly increased by optical or electrical amplification The amplification however is limited by the signal to noise ratio Thus if environmental vibrations (for optical recordings) or electronic noise (for electrical amplification) become so large that they begin to distort the signal the practical limit is reached The problem cannot be attacked by making the mechanical devices (flow cannulae membranes galvanometers) extremely sensitive because their frequency response decreases when sensitivity is increased The range of compromise between adequate frequency response and sensitivity is very narrow when differential flow recorders are used in the venous system

A serious challenge to the validity of flow measurement by differential pressure flowmeters has been voiced by Spencer and Denison (1956) and by Richards and Williams (1953) Using an electromagnetic flowmeter they could not confirm the existence of a phasic flow reversal at the end of systole in the carotid and femoral arteries as had been reported by Shipley et al (1943) who worked with an orifice meter When Richards and Williams produced a strong resistance to flow by applying a cuff distal to the electromagnetic flowmeter they created a flow pattern showing the rever e flow which Shipley et al had demonstrated They concluded that the back flow recorded with an orifice meter may be an artifact produced by the resistance of the flowmeter

Their deduction however may not be valid When an inflated cuff is applied around an artery distal to the electromagnetic flowmeter the vessel segment between flowmeter and cuff distends during systole like a compression chamber During diastole the elastic force of the distended arterial wall causes a local reflux of blood through the electromagnetic flowmeter Actually the resistance produced by a differential flowmeter is not distal to but right at the points of the pressure pickups This would cause a distension of the arterial wall proximal to the flowmeter and hence could not produce back flow through the flowmeter during diastole Since this is an essential question concerning the accuracy of phasic flow measurements in arteries as well as in veins another explanation should be ought

The apparent back flow could be an artifact created by the acceleration factor in the differential quotient of Otto Frank (1929a 1930) At high flow acceleration this factor can increase the signal deflection beyond the actually existing flow velocities This signal deflection for differential flowmeters depends not only on the velocity (kinetic energy factor) but also on the *rate* at which the velocity changes (acceleration factor) If for example the flow velocity decrea ed uddenly at the fir t pressure pickup the fluid column between the two measuring points would still communicate and owing to its inertia this blood would exert excessive pres ure on the second measuring point This should not occur if both pickups are in the same cross sectional plane of the vessel By arranging Pitot pres ure pickups in the same plane Alois Muller and his a ociates (1948 1954a) demonstrated that the acceleration factor and thus any back flow artifact would indeed become insignificant

The Pitotmeters u ed in the experiments reported here suffered from an over

shoot' of the signal deflection caused by the inertia of the manometer fluid column and by the acceleration factor. For this reason records taken with these instruments permitted the study of slow respirogenic changes of flow but not that of fast cardiogenic changes. Since the overshoot was empirically determined to be of approximately equal magnitude in both directions (for forward and backward flow) it could be cancelled out in the analysis of the records for slow changes (Mixter 1953, Brecher and Mixter 1953, Brecher 1953).

Summarizing

Adequate construction of differential flowmeters can minimize or abolish the acceleration factor which otherwise may distort phasic flow curves and simulate a back flow.

Pendulum Flowmeters

The principle of the pendulum flowmeters consists of the introduction of a small pendulum paddle reed wire or bristle into the bloodstream. The flowing blood deviates the pendulum from its resting position. The deviation is proportional to the velocity of the blood stream.

This hydrodynamic principle was introduced by the Italian engineer Castelli (1577–1644), a student of Galilei (Muller 1954b). Vierordt applied it in 1858 to the measurement of blood velocity (hydrometric pendulum). Chauveau (1860) and his student Lortet (1867) developed the hemodromograph with which they recorded phasic flow and pressure in arteries simultaneously. The principle was again advanced by Otto Frank (1928 and 1929b) but not further employed until de Burgh Daly developed in 1930 a flowmeter which measured electrical capacity changes induced by shifts in pendulum position. Again this information was forgotten and remained unknown to Bergman (1938), Holzlohner (1938) and Holzlohner and Schoenstedt (1940) when they developed their bristle tachograph. They measured the electrical resistance between the platinum tip of a moveable glass bristle and a fixed platinum electrode in the flow cannula, this resistance varying with changes in the amount of blood (distance) between the contacts. By using the curvilinear limb of the bridge balance curve they produced a linear calibration curve. Unreliable drift and uncontrollable resistance changes due to minute fibrin deposits or other impurities at the platinum tip of the bristle are the main objections to this method. (For criticism see Pieper and Wetterer 1953.)

(a) *Electromagnetic pendulum.* In electromagnetic pendulum flowmeter the pendulum is made of ferromagnetic material which moves in an induction field. The inductance changes are then amplified. We constructed a sensitive flowmeter of this type by winding two induction coils of 450 turns each around a plastic cannula into which a pendulum eight mm long, containing approximately 100 mg of iron protruded (Crum 1952). The signal to noise ratio was high and drift due to temperature changes amounted to as much as 10 per cent of the signal strength. Scher et al. (1953) constructed a similar device using a paddle shaped ferromagnetic pendulum with only a few coil winding resulting in low sensitivity but good temperature stability.

Pieper and Wetterer (1953) solved the stability problem successfully by

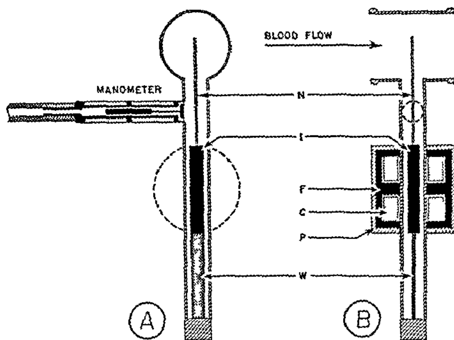


FIGURE 14 Schematic diagram of electromagnetic pendulum flowmeter for simultaneous measurement of flow and pressure A = Cross section showing a miniature manometer inserted at the side of the T segment of the flow-cannula B = Cross-section at 90° to A showing arrangement of electromagnet and horizontal segment of T-cannula which is inserted into blood vessel N = needle I = induction metal F = ferromagnetic core C = coil P = plastic cover and W = watch spring Proportions not to scale Maximal dimension [illegible]0 mm (Redrawn from Pieper and Wetterer 1953)

placing the iron mass in the lower part of a long pendulum which protrudes from a T cannula into the blood stream (Fig 14) The induction coils are wound around the vertical part of the T cannula and are not much affected by temperature changes of the blood which streams through the horizontal part The natural frequency of this flowmeter is 200 cycles/sec Though employed by Pieper and Wetterer *in arteries this instrument would be very suitable for venous flow* recording since it offers practically no resistance to flow is sensitive and of small dimensions Unfortunately the intricate flow sensing element must be home made

(b) *Bristle flowmeter* Many studies reported in this book were undertaken with the aid of the bristle flowmeter developed in our laboratory (Brecher and Praglin 1953 Brecher 1954) *The flow* sensing element is a subminiature vacuum tube (Radio Corporation of America No 5734 mechanoelectronic transducer) The great constructional advantage of this bristle flowmeter is the commercial availability of the flow sensing element which merely needs to be incorporated into a suitable cannula Scher et al (1953) simultaneously constructed the same type of flowmeter

A schematic diagram of the bristle flowmeter is shown in Fig 15 The 5734 tube is held in a screw base B and A Part I connects the screw base with the

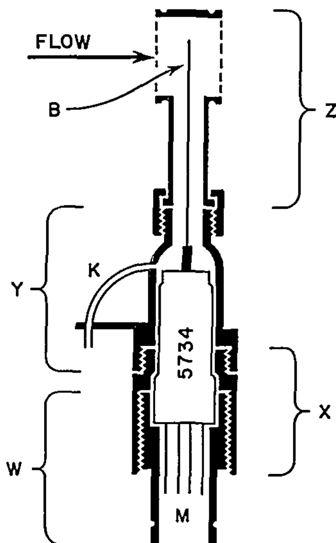


FIGURE 15 Schematic diagram of bristle flowmeter cannula utilizing a 5734 subminiature vacuum tube as flow sensing element Total length of cannula 50 mm Description in text

head of the cannula *Z* which is inserted into and ligated to the vessel 'Heads of various dimensions can be used with the same flow cannula for different sized vessel Side tube *K* serves for removal of air bubbles, flushing and pressure recording The blood stream deviates a small bristle (B) which is attached to the plate pin of the vacuum tube The bristle acts as a lever and its deviation is proportional to the flow velocity The plate pin extends through a flexible metal diaphragm into the inner part of the vacuum tube The metal diaphragm thus acts as a fulcrum the inner part of the plate pin is the anode When the bristle is deviated the electron current from cathode to anode varies in proportion to the distance between them which is determined by the degree of deviation The electrical signal is amplified and recorded with a suitable high frequency mirror galvanometer on a photokymograph or with another indicating device

The natural frequency response of the 5734 tube is 12 000 cycles/sec The response is decreased by attaching the bristle the decrease depending upon the length and the mass of the attached piece Using a filament about 38 mm in length a natural frequency response of 125 to 200 cycles/sec can be attained In combination with a specially designed amplifier and power supply the bristle flowmeter has very little electronic drift and a high signal to noise ratio Without decreasing the high fidelity of the moving mechanical parts of the instrument the pulsating flow signal can be electrically integrated in the amplifier circuit (Praglin and Brecher 1955) The bristle flowmeter has the following advantages which make it especially suitable for recording rapid fluctuations of flow in veins (1) negligible resistance to blood flow (2) high fidelity (3) great and variable sensitivity (4) compactness (5) absence of turbulence over a wide range of flow rates (6) equal response to forward and backward flow and (7) negligible base line drift

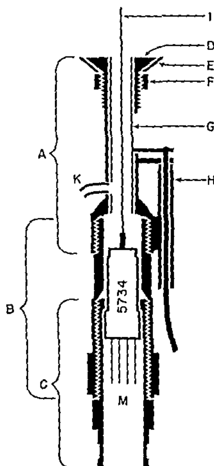


FIGURE 16 Cross section of bristle flowmeter modified for use in the pulmonary artery trunk for determination of the right heart stroke volume Total length of cannula 5 mm Description in text

A special modification of the bristle flowmeter has been developed for direct recording of right cardiac output (Brecher and Hubay, 1954). This enables simultaneous study of the hemodynamics of cardiac inflow and outflow. Figure 16 shows a diagram of the flowmeter cannula and Figure 17 an artist's concept of its position in the pulmonary artery. The device consists of parts *A*, *B*, and *C*. The tip of part *A* in inserted into the vessel wall by slipping the lip *D* through a "buttonhole" opening in the arterial wall. Lip *D* is secured to the intima by the pressure of plate *E* on the outside of the wall. Plate *E* is held in place by screw *F*.

A cylinder *G* can be pushed forward or retracted by means of a cable release *H*. When the cylinder *G* is in the retracted position as shown in Figure 16, the

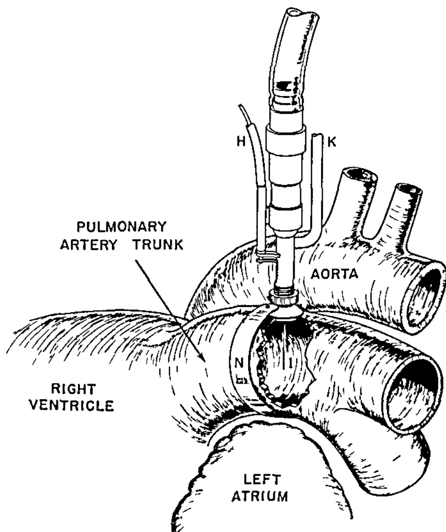


FIGURE 17 In situ diagram of the bristle flowmeter which is depicted in Figure 16. It illustrates the flowmeter's position in the pulmonary artery. H = cable release for advancing and retracting zeroing cylinder. K = side tube for recording pressures and removing airbubbles. I = bristle and N = metal band which fixes the circumference of the pulmonary artery trunk by passing around the vessel. The zeroing cylinder is not visible because it is retracted.

bristle I can be deviated by the blood stream When the cylinder is pushed forward beyond the bristle tip it protects the bristle from deviation by the current This cylinder for producing zero flow has proven to be very valuable for maintaining physiological circulatory conditions It permits frequent inscribing of zero flow in any segment of a record to check on electronic drift without the necessity of interrupting blood flow by clamping the vessel This is particularly important in the pulmonary artery trunk where temporary occlusion of the vessel may overdistend and damage the right ventricle

Pulmonary artery pressures are obtained through tube A Part B is a long threaded shaft into which part C can be advanced by turning Part C serves as a socket for the RCA 5734 vacuum tube M indicates the leads to the recording instrument The bristle is protected from damage during the insertion by turning part C until the tip of the bristle is retracted behind lip D After insertion through the pulmonary wall the bristle is advanced into the lumen of the pulmonary artery by turning part C A metal band N is placed around the vessel in order to fix the artery s diameter as illustrated in Figure 17 This is indispensable for quantitative flow measurements The flowmeter must be calibrated in situ after the experiment

The advantages of this modified bristle flowmeter are the following (1) It permits faithful recording of pulmonary artery flow and its fluctuations from one heartbeat to the next (2) It can be inserted with a minimum of trauma into the pulmonary artery trunk without blood loss and without interrupting flow (3) Since the electrical mean averages all actual forward and backward flow at the site of the flowmeter it records what is conventionally defined as cardiac output

A typical calibration curve of the bristle flowmeter is depicted in Figure 18 The calibration curve follows approximately a square function (For details concerning the relation of bristle deflection and fluid velocity see Muller 1954b)

The calibration is done either in situ or with the aid of tubes by passing steady or pulsatile currents of blood from a reservoir through the flowmeter The calibration curve must be empirically determined for each experiment As designed in the amplifier (Praglin and Brecher 1955) the calibration for pulsatile and average flow is identical This permits switching from the recording of pulsatile to mean flow during the experiment

(c) *Strain gauge pendulum flowmeter* A strain gauge wire 8 mm long is firmly fastened to a trapezoid shaped pendulum 4 mm long The deviation of the pendulum stretches the strain gauge wire and the ensuing resistance change is used to produce an electrical signal The main advantage of the instrument is its small size It can be advanced through a 13 gauge needle into the vessel to measure blood velocities Though the instrument is still in a developmental stage it may have a promising future (C R Honig personal communication)

Summarizing

Among the various pendulum flowmeters which have been developed, the 5734 bristle flowmeter utilizing commercially available parts, is the easiest to con

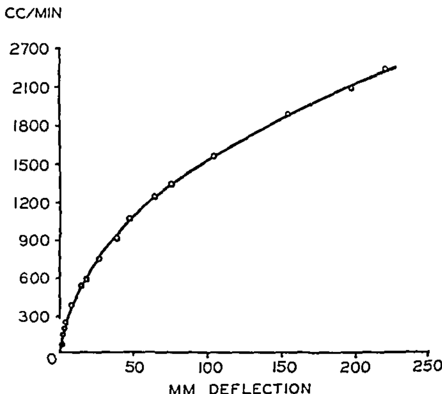


FIGURE 18 Calibration curve of bristle flowmeter For flow in the reverse direction the curve is symmetrical to the curve for forward flow

struct It permits faithful recording of rapid flow changes in veins of experimental animals

Critique of Pendulum Flowmeters

For several reasons pendulum flowmeters have enjoyed little popularity in the past but have recently been judged quite useful

1 Their sensitivity depends principally upon the form of the pendulum The larger the obstruction to flow the greater the sensitivity but the poorer the fidelity because of the pendulum mass If the obstruction is large as by a broad paddle the deflection of the pendulum is approximately proportional to the square of the velocity The resulting calibration curve is thus nonlinear If the obstruction is very small as by a thin filament the deflection of the pendulum is almost proportional to the velocity and the calibration curve approaches linearity (see also Muller 1954b) A suitable pendulum usually incorporates a compromise between sufficient sensitivity and adequate frequency response In the hemodromograph of Chauveau and Lortet high fidelity and low resistance had to be sacrificed in favor of sufficient sensitivity This dilemma could not be overcome until very sensitive electrical transducers were developed The high sensitivity of the 5734 subminiature vacuum tube and Pieper's and Wetterer's electromagnetic transducer has given a special impetus to the development of modern pendulum devices

2 A great advantage of the pendulum flowmeters is their small size and com

pactness The segment of the cannulated vessel which is fixed by the ring like structure of the cannula head is only a few millimeters in length This assures a minimal interference with the normal flow dynamics The instrument can be easily inserted into short segments of vessels in tight corners the chest abdomen or other tissues can be closed and resume their normal anatomical position

3 The acceleration factor of Otto Frank which plays an important role in differential pressure flowmeters (see page 41) is negligible in pendulum flowmeters

4 A disadvantage of the pendulum flowmeters is the weight of the pendulum itself In a sensitive instrument gravitational effects created by an alteration of the position of the flowmeter produce a change of electrical signal The instrument must therefore be firmly clamped during an experiment

5 Further disadvantages of pendulum flowmeters are the necessity of using anticoagulants and of opening the vessel for the insertion of the bristle With adequate heparinization and coating of the instrument with silicone we have never observed any fibrin deposit on the bristle or flow cannula

Summarizing

Pendulum flowmeters have adequate sensitivity and fidelity only by virtue of very sensitive tranducers Compact pendulum devices do not distort flow dynamics The necessity of cannulization limits their use

OTHER PHASIC FLOWMETERS

Brief mention should be made of several other flowmeters which have not yet been used for recording of phasic changes of venous flow but which offer future possibilities

(a) *Electromagnetic flowmeter* Electromagnetic flowmeters have been used successfully for pulsatile flow recording in arteries (Kolin 1936 Katz and Kolin 1938 Wetterer 1937 Wetterer and Deppe 1939 Deppe and Wetterer 1939 1940 Wetterer 1940 1954 Jochim 1948 Richards and Williams 1953) The main disadvantage of the electromagnetic flowmeters is their low signal to noise ratio

One must distinguish three types of electromagnetic flowmeters (1) *The direct current meter* This was used in various forms by Kolin (1936) Wetterer (1937) Jochim (1948) and Richards and Williams (1953) It suffers from an interference of the flow signal by random polarization voltage (2) *The sine wave current meter* Kolin (1941 1945 1952) removed the polarization of the electromagnetic field by applying a sinusoidal alternating current to the magnet However the alternating current induces in the electrodes a voltage which interferes with the flow voltage (Richardson Denison and Green 1952) (3) *The square wave current meter* Denison Spencer and Green (1955) overcame the difficulties of the sine wave current by applying a square wave alternating current The magnetically induced voltage from this current forms induced spikes which are removed by a chopper in the amplifier Spurious voltages and interference by electrical artifacts (ECG) have been greatly reduced by increasing the magnetic flux (saturating the magnet) and by increasing the square wave

alternating frequency In its latest version the flowmeter permits faithful recording of phasic flow, as it has an upper limit of frequency response of over 100 cycles/sec (Spencer and Denison, 1955)

The electromagnetic flowmeter meets with some difficulties in the venous system particularly in the central veins In arteries, the firm electrode application is assured by a gentle compression of the vessel In the collapsible veins such procedure would not be feasible It may however be possible to fix the cross sectional area and position of the vein in the magnetic field by surrounding the vessel with a ring like suction sleeve which prevents collapse of the walls Strong ECG currents may also interfere with the flow signal in central veins Nevertheless the great advantages of the electromagnetic flowmeter especially in its late form (Spencer and Denison 1955) may make it the instrument of choice for the future Its main advantages are (1) quantitative measurement of phasic flow in intact vessels without the use of anticoagulants (2) linear calibration (3) equal response to forward and backward flow, (4) small size and compactness of the flow sensing unit

(b) *Diathermy thermostromuhr* This method and some unwarranted claims which have discredited the thermostromuhr for use at the unopened vessel were discussed in detail by Gregg (1948) Even the modification and improvement of the thermostromuhr by Oberdorf and Wilcke (1954) have not removed the inherent calibration difficulties New perspectives have been more recently opened by reinvestigation and modification of the thermostromuhr principle

Following a study of Aschoff (1955) on the heat transfer to streaming blood Wever (1955) Aschoff and Wever (1956) and Wever and Aschoff (1956) investigated the applicability of the diathermy thermostromuhr to unopened vessels Using a diathermy frequency of 200 to 300 kilocycles/sec they found that 80 per cent of the energy goes to heat the wall and not the blood column The wall is warmed asymmetrically that is more downstream than upstream The heating of the upstream portion of the wall is little affected by the blood flow However the downstream temperature depends greatly upon the volume flow of blood mainly because blood cools the downstream portion of the vessel wall The temperature changes are rapid but still too slow for faithful recording of very fast changes in bloodflow Though the signal to noise ratio of the diathermy stromuhr is better than that of the square wave electromagnetic flowmeter it may be less applicable to central veins because of the slow response Probably its best suited function is the measurement of flow in unopened peripheral vessels

(c) *Catheter thermostromuhr* Another recent modification of the thermostromuhr appears promising for venous flow recording in larger unopened vessels Kanzow (1955) constructed a thermostromuhr which is incorporated into the tip of a catheter It can be inserted from the external jugular vein into the coronary sinus of a dog without opening the chest Six short heating elements in the wall of the catheter tip are cooled by the coronary sinus blood An inflatable balloon near the catheter tip insures that all coronary sinus blood passes by the thermodes The blood then drains from the catheter lumen into the right atrium through holes in the catheter wall This instrument also in its present form suffers from a limitation of frequency response

(d) *Thermistor flowmeter* A different type of a thermostromuhr is based on the principle of thermistors which are cooled by the streaming of blood The thermistor flowmeter of Felix and Groll (1953) and Felix (1955 1956) has a number of advantages The flow sensing element the thermistor is commercially available (Phillips Co) The thermistor is a very small resistor which alters its electrical resistances with temperature changes The mass of the thermistor is so minute that when it is inserted into the blood stream the element responds fully to a temperature change within 1/20 sec

The thermistor forms one of the arms of a Wheatstone bridge Owing to the extreme sensitivity of the device for slow flows no amplication of the signal is needed Zero drift of the baseline is absent It is ideal for the study of minimal flows The disadvantages of the device are as follows (1) It cannot distinguish between forward and backward flow (2) The calibration is logarithmic showing great sensitivity for low flows and little sensitivity for high flows Thus the tracing for zero flow cannot be included on the record and the calibration is cumbersome (3) The vessel must be cannulated for a considerable distance for calibration purposes Nevertheless owing to its great simplicity and sensitivity the thermistor flowmeter may become a suitable instrument for the measurement of small flow volumes in peripheral vessels of experimental animals when the possibility of back flow is excluded

(e) *Electrosonic flowmeter* The electrosonic flowmeter can be used on unopened vessels (Kalmus 1954) It is based on the principle of the phase shift of ultrasonic sound at different flow velocities It is moderately compact has adequate sensitivity and a high frequency response The electronic signal detector is rather complicated Theoretically the instrument should have good prospects for venous flow recording

Summarizing

The electromagnetic and electrosonic flowmeters may permit recording of rapid phasic flow changes in unopened veins The diathermy and catheter thermostromuhr appear suitable for measuring moderately fast changes of flow in unopened veins The thermistor flowmeter is very sensitive and stable for recording of small volume flow in cannulated veins

Indirect Methods

Except for isolated problems indirect methods do not at present furnish sufficiently accurate information for a quantitative study of venous return However investigators will always strive for perfection of indirect methods because in many instances these are the only ones which can be applied successfully to human beings and animals under physiological conditions Since it is beyond the scope of this monograph to review the literature on this rapidly progressing and highly technical subject only a few recent advances should be pointed out which open new perspectives (For the older literature see Franklin 1937)

In the future the answer to many questions will be provided by high speed direct and x ray cinematography of the movement of blood in veins (For technique and results consult Bohme 1936 Laszt 1949 Gohrbandt et al 1953 Lind et al 1955) The quantitation of the velocity measurements in terms of

volume flow offers a particularly difficult problem (McDonald, 1952 Helps and McDonald 1954 McDonald, 1954 McDonald 1955, Womersley, 1955 Hale, McDonald and Womersley 1955 and personal communication of McDonald) In addition to their remarkable contributions McDonald and his co workers have also pointed out the technical difficulties and limitations of the present cinematographic methods of angiography

Introduction of foreign material such as air bubbles iodopine drop etc for flow quantitation meets with several theoretical objection Quantitation of pulsatile volume flow is best accomplished by an analysis of the moving front of the injected material (dye or x ray opaque fluid) Only at this region are differences of optical density between blood and the contrasting material strong enough for visualization However the border of the contrasting medium is very indistinct *The borderline becomes even more diffused by pulsatile velocity* changes (Fig 19)

During a period of forward flow (Fig 19A) the paraboloid cone of the axial stream greatly precedes the marginal stream When the fluid column reverses during a period of backward flow (Fig 19B) the flow reversal is greater for the axial stream than for the margin Thus looking through the intact vessel from the side part of the axial stream appears to be enveloped and consequently ob

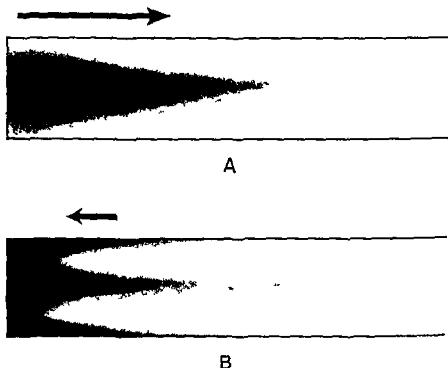


FIGURE 19 Visualization of the optically diffuse border in the flow profile of contrast material in a vessel during (A) forward flow and (B) a brief period of backward flow The diagram shows only a section through the longitudinal midplane of a schematic vessel (Drawing based on concepts evolved by McDonald)

secured by the dense cylinder of the marginal stream which undergoes little or no backward movement The cro ection in Figs 19A and B should be visualized three dimensionally to appreciate the difficulty of tracing the movement of blood through the cro sectional area of an intact vessel e pecially if the vessel changes its shape from moment to moment For flow quantitation in veins stereo cinematography or taking pictures of the ve sel from two planes at right angles may offer better chances for analy is

Further progress in high speed x ray cinematography of unexpo ed ve sels in situ may be expected by the employment of special cameras (Gohrband et al 1953) and of x ray intensifiers such as those made by Phillips and Westing house (Lind et al 1955 Ardran and Wyatt 1954)

Summarizing

Quantitation of phasic flow changes in veins by the use of indirect methods is technically difficult becau e at present it is not po ible to obtain the neces sary preci ion for visualization of changes in volume flow

VI Venous Hemodynamics

The special features of venous flow dynamics are mostly due to the collapsibility of the veins For a basic understanding it is therefore, best to examine flow through structures that are similar in shape to partially collapsed vein

Modification of Poiseuille's Law

Volume flow through a tube or vein of an elliptic cross sectional area can be calculated by the following modification of Poiseuille's formula (Acher and Spurgeon, 1949 Milne Thomson 1950)

$$Q = \frac{\pi\ a^3\ b^3(p_1 - p_2)}{\eta(a^2 + b^2)4l}$$

In this equation all factors are the same as defined in Poiseuille's formula (page 11) except for r^4 which is replaced by

$$2\left(\frac{a^3\ b^3}{a^2 + b^2}\right)$$

This expression refers to the two different diameters of the elliptic cross sectional area a = the minor semi axis and b = the major semi axis of an ellipse

For an understanding of the effect of the two semi axes on flow the two extreme cases of an ellipse should be considered first In a circle (an ellipse with both semi axes equal) a and b would have equal value a = b = r and it is readily seen that flow through such a vein would be maximal or unity compared to that through any other possible ellipse On the other hand in the flattest ellipse (a line of the extension of the major semi axis b) the minor semi axis would equal zero Thus flow would be zero through a vein with no minor axis (completely collapsed)

Hence flow through a vessel of any elliptic cross sectional area between these two extreme cases can be graphically represented as a function of the minor semi axis of an ellipse is plotted in Fig 20 The three graphs show the effect on flow of varying the minor axis while keeping constant (A) cross sectional area (B) perimeter or (C) major axis The examples in Fig 21 help to illustrate the graph of Fig 20

Curve A of Fig 20 is a plot for flow through elliptic tubes of constant cross sectional area In Fig 21 flow through a round tube (A) is compared with that through an elliptic tube of the same crosssectional area (B) when the minor semi axis is decreased to half of unity It is noted that flow through the elliptic tube is less than half of that through the round tube although both tubes have identical crosssectional areas This example illustrates that a mere change in the form of a vessel without decrease of crosssectional area reduces flow

It is obvious that with the elliptic flattening the major diameter must increase in order to keep the crosssectional area constant This would however not be the case when a vein undergoes partial collapse and the minor semi axis of its

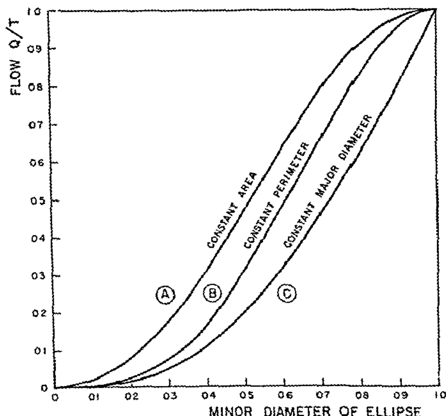


FIGURE 20 Graphic representation of volume flow (ordinate) through elliptic tubes as a function of the minor semi axis of the elliptic cross-sectional areas (abscissa) With a decrease in the minor semi axis the area (Curve A) perimeter (Curve B) or major semi axis (Curve C) of the ellipses are kept constant A minor semi axis of unity is the radius of a circle

cross-section decreases The configuration of a collapsed vein would correspond closely to an ellipse with a constant perimeter and a smaller crossectional area

In curve B of Fig 20 flow is plotted for ellipses of constant perimeters The example in Fig 21C shows that flow through an elliptical tube (minor semi axis half of unity) amounts to less than one third of that through a circular tube of an identical perimeter (A) It should be pointed out that veins do not always maintain the same perimeter when they undergo partial collapse but may occasionally approach configurations which correspond to ellipses in which the major diameter does not change

Curve C in Fig 20 is a plot for flow through ellipses with constant major semi axes The example in Fig 21D illustrates that flow through an elliptic tube with a major semi axis of unity and a minor semi axis of half unity is only one fifth of that passing through a circular tube of the same radius as the major semi axis (A)

From these considerations one may conclude that other factors remaining the same flow would be reduced to about one fourth if during semi collapse

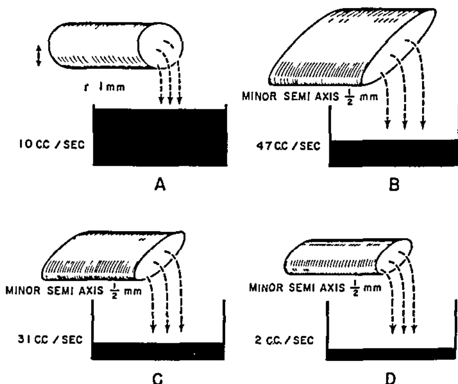


FIGURE 21 Effect of the shape of a tube's crossection on flow (A) Flow through a tube of circular cross section of 1 mm radius yields 10 cc/sec (B) Flow through tube with the same cross sectional area as in (A) but of elliptic shape with a minor semi axis of ½ mm yields 4.7 cc/sec (C) Flow through tube with the same perimeter as in (A) but of elliptic shape with a minor semi axis of ½ mm yields 3.1 cc/sec (D) Flow through tube with the same major semi axis (1 mm) as the radius in (A) but of elliptic shape with a minor semi axis of ½ mm yields 2 cc/sec Flow through a vein in a semi-collapsed state would correspond approximately to C or, if the perimeter becomes smaller, to that through a tube intermediate between C and D

a round vein assumes an elliptical crossection with a minor semi axis equal to one half the radius of the circular vein More extensive collapse of the veins than this is frequently observed It occurs rapidly or slowly intermittently or continuously as collapse is occasioned by changes of intravascular and extravascular pressures (e g during the heart cycle the respiratory cycle movement of the body or due to venomotor mechanisms) The amount of the flow reduction for any degree of venous collapse can be readily estimated by consulting the curves in Fig 20

Since flow through a partially collapsed vein (elliptic tube) is reduced while the perfusion pressure remains the same resistance to flow through a partially collapsed vein must be greater than that to flow through a round vein Thus the curves in Fig 20 can also serve as a plot of the resistance to flow through elliptic tubes (veins) if one substitutes Q in the ordinate by $1/R$ (R = resistance) As we shall see later the fundamental relations represented in Fig 20 serve to explain the flow changes through collapsing veins observed in vivo

Summarizing

Volume flow through partially collapsed veins obeys approximately the laws of flow through tubes of an elliptic crosssectional area When pressure remains constant volume flow through a vein in a semi collapsed state is about one quarter of that through the same vein when it is round

Pressure Gradient Along Central Veins

The pressure gradient throughout the entire vascular system from the root of the aorta to the right ventricle is very great The steepest pressure drop occurs in the arterioles the place of the highest resistance The pressure gradient throughout the venous system is small since the resistance is low especially in the central veins Therefore pressure differences of only a few mm of water are sufficient to drive large quantities of blood through the central veins Unquestionably pressure differences of a few mm of water suffice to drive the same quantity of blood through the central veins that is propelled through the aorta since essentially the same amount of blood that is expelled must also enter the heart

The extensive literature on the subject reveals the difficulty of recording accurately the e minute pressure differences Failure to detect any gradient has even led to suggestions that there is no pressure difference in central veins Obviously this is physiologically impossible because blood cannot flow without a pressure difference whatever its origin be it the *vis a tergo* or the *vis a fronte* or a combination of both

Failure to demonstrate a pressure gradient along the central venous bed may be attributed to several causes (1) As Henderson and Barringer noted (1913) the uncertainty of making reliable venous pressure measurements is due to the fact that the slightest compression or stretching of the tissues through which the vein passes is sufficient to collapse it The reading on the manometer may thus easily be elevated many centimeters above the true pressure or depressed as much without the observer being led to suspect the error (2) When pressure is measured simultaneously at two points in a vein a difference of a few millimeters in the hydrostatic level of the openings of the two pressure pickups can simulate absence or reversal of the pressure gradient (3) Due to high peak velocities in the central veins potential energy (measured as lateral pressure) is low and kinetic energy (energy of flow) is relatively high (see also Fig 4D) In the right atrium kinetic energy may in part be reconverted into potential energy which would result in the recording of a higher lateral pressure than in the vein Particular attention must therefore be paid to the position of the pressure recording tip in veins because of the Bernoulli effect

Semba and Kishi (1953) measured meticulously the mean venous pressure gradient along the caval veins in dogs and arrived at the following conclusion

The fall in pressure of the thoracic vena cava is trifling which shows that blood is stagnant in the central vena cava and has formed a pool The fact that the central venous pressure gradient is indeed very small can be accepted but it is erroneous to conclude from this observation that blood is stagnant Actually the greatest flow velocities in the venous system occur in the caval veins as

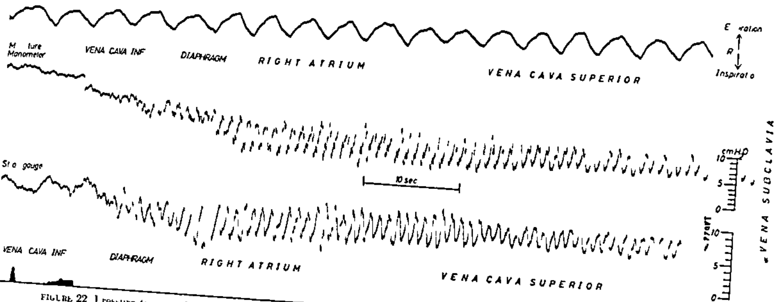


FIGURE 22 Pressure tracings from the central veins of a normal unanesthetized person illustrating the smallness of the pressure gradients along the thoracic inferior and superior venae cavae Upstrokes in the phasically changing pressure curves are caused by atrial systoles Description in text (Original Unpublished record by courtesy of Gauer and Sieker 1956)

we shall see later The fallacy of the above statement merely emphasizes that one cannot draw conclusions about blood flow from pressure measurements alone

In the unanesthetized human Gauer and Sieker (1956) accurately recorded phasic pressures with a very sensitive high fidelity miniature manometer in order to establish the pressure gradient along the central veins (Fig 22) They pulled a double lumen catheter at a constant rate of 5 mm / sec from the abdominal vena cava through the right atrium up to the subclavian vein The fluid column from the tip of the catheter was connected to a conventional strain gauge manometer, whereas the miniature manometer was situated 23 mm behind the tip Hence the two venous pressure tracings (and their labeling) are displaced by 4 6 seconds on the time scale (middle and lower curve) The curves reveal the existence of an easily measurable pressure gradient from the abdominal inferior vena cava through the liver region (labeled diaphragm) to the atrium On the other hand they show that a pressure difference of *only* a *few* mm of water exists between the thoracic portions of the caval veins and the right atrium These findings demonstrate that in man as in dogs the pressure gradient along the thoracic caval veins is so small that it is very difficult to establish manometrically

Summarizing

Owing to the low resistance a small pressure gradient suffices to propel large quantities of blood through the central veins Thus the pressure gradient along the central venous bed is so small that it is difficult to record It can be misleading to draw conclusions from differences of pressures when investigating volume flow in the veins close to the heart

PRESSURE FLOW RELATIONS IN COLLAPSIBLE VESSELS

We shall now consider the *changes* of flow resulting from variations in pressure gradients along veins in order to establish the *dynamics* of pressure flow resistance relations during collapse of the veins in the living organism A detailed analysis of these relations is called for since flow through collapsible tubes is a subject which has been somewhat neglected by physicists

First a word about the precise meaning of the term collapse which is so frequently used with differing connotations[1] In the Holt Duomarco terminology, collapse refers to any state of the vein in which its crosssectional area is not circular but has assumed an elliptical configuration In ordinary usage 'collapse' is often associated with a complete closure of the vein For greater precision the term partial collapse is used herein for any state of a vessel which still permits the passage of fluid (limbs of the curves in Fig 20 beyond zero) and 'complete collapse when it is flattened to such a degree that no fluid passes through it (point zero in Fig 20)

Several problems concerning the effect of the venous pressure gradient on flow were studied in detail in our laboratory (Brecher 1952) This was done by examining phasic changes of flow in the superior vena cava system of dogs with the chest open All factors but one the pressure gradient were held constant

Figure 23 shows a schematic diagram of the experiment The animals were in supine position with the external jugular veins and heart on the same level

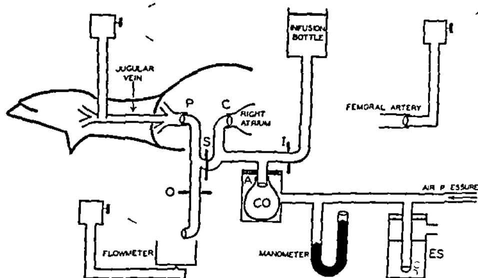


FIGURE 23 Experimental arrangement for measuring drainage from superior vena cava Points O S and I indicate where clamps are applied Clamp S is closed clamps O and I are opened for outflow measurement and simultaneous compensation of right atrial inflow CO = constant pressure blood reservoir ES = escape valve Description in text

The superior vena cava was cannulated (P and C) permitting flow either through a *shunt S to the right atrium or through an outflow tube O to a cumulative flow* meter of the type shown in Fig 8 Reduction of the cardiac output through loss of blood was prevented by simultaneously infusing an equivalent amount of blood into the right atrium from a low pressure reservoir *CO* Different pressure gradients were applied to the entire superior caval system by setting the outflow cannula at different levels and recording ouflow at each level for 10 seconds The level of the outflow cannula ranged from 200 mm above to 600 mm below the level of the jugular vein which is the reference or zero level The procedure allowed flow measurment when the veins were either distended or as a result of suction collapsed in varying degree

Obviously the abrupt changes of the venous pressure gradient and maintainance at a definite level which were produced in these experiments do not occur physiologically This strictly controlled arrangement was however necessary for the investigation of the physical factors determining venous flow dynamics

Figure 24 shows 6 records of a typical experiment demonstrating the relation between pressure gradients and vena caval outflow *

Figure 24A shows the effect of raising the outflow level from 0 to +60 mm Pressure measured in the external jugular vein rose steeply within two seconds from 39 to 68 mm As expected no flow occurred until a sufficient amount of blood had accumulated in the veins to raise jugular pressure above the height

* In this and all other experiments reported from our laboratory the pressures were recorded with modified Gregg optical manometers For better reproduction the tracings in some of the original records from our laboratory have been reenforced

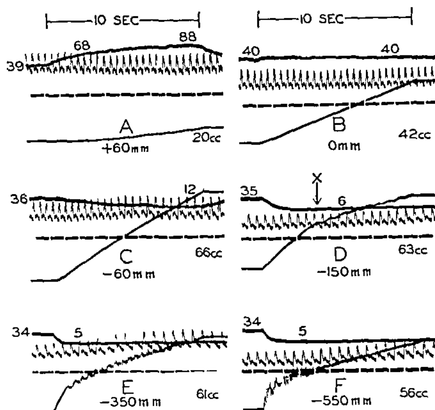


FIGURE 24 Six records illustrating the effect of the pressure gradient upon outflow from the superior vena cava system Tracings from top to bottom in each record jugular pressure femoral arterial pressure base line with time in seconds cumulative blood flow Calibration jugular pre ure in mm water flow in cc during 10 sec periods arterial pressure in mm Hg with a range of 128/98 to 117/96 The high frequency oscillations in the flow tracings of records E and F are due to spurts of blood setting the flowmeter into vibration

of the outflow tube Then flow commenced lowly at first then at a fa ter rate (steeper lope) as jugular pre sure rose gradually from 68 to 88 mm The total flow amounted to only 20 cc in 10 seconds

Figure 24B illustrates the behavior of flow and venous pres ure when the outflow tube was at the jugular atrial level Venous pressure remained constant before during and after measurement of flow indicating that during the outflow period re i tance to flow remained unaltered Flow started immediately with the opening of the outflow tube and continued at an unchanged rate as evi denced by the constant lope of the flow tracing The total flow was 42 cc in 10 second

Figure 24C hows the effect of lowering the outflow level from 0 to −60 mm During the outflow period venous pressure fell steadily from 36 to 12 mm of water Flow began at a fa t rate and then decreased slightly Total flow amounted to 6)9 cc in 10 econd

Quite different results were obtained when suction was increa ed from 0 to

−150 mm is shown in Fig 24D Venous pressure decreased within 3 5 seconds *from 36 to 6 mm of water and then leveled off, never falling below zero Flow* started at a high rate but decreased gradually Suddenly at X the steady flow stopped momentarily and became pulsatile as indicated by the wavelike tracing Immediately after the onset of pulsations flow was greatly reduced The frequency of the pulsations was not related to the heart rate Total flow during a 10 second period (63 cc) had not increased in spite of the greater pressure gradient

Records E and F of Fig 24 depict the effects of further increase of suction In both cases a steep fall of venous pressure took place Flow commenced with a large gush of blood then pulsations (chatter) occurred due to the intermittent collapsing of the venous walls Total flow amounted to 61 and 56 cc respectively

It appears from these records that increase of suction results in a decrease of the rate of volume flow due to partial collapse of the veins

The pressure flow relations established in this type of experiment are graphically presented in Fig 25 (data from another animal) In curve A flow in cc 10 sec (ordinate to the right) is plotted against the pressure gradient (mm water abscissa) between the external jugular pressure and the level of the outflow tube above and below the level of the jugular vein It is noted that when the level of the outflow tube is 120 mm above the jugular vein outflow is zero and the superior cava becomes engorged This congestion is likewise indicated by the jugular vein pressures (ordinate left) before the 10 sec flow period (curve B in Fig 25) and during outflow (curve C in Fig 25) During congestion jugular venous pressure rose from 39 mm to almost 120 mm of water (point not on graph) When the outflow tube was at the same level as the jugular vein outflow was 44 cc in 10 seconds and the jugular pressure remained practically unchanged (crossing of curves B and C) The largest flows (70 cc) were obtained when the outflow tube was 100 mm below the level of the jugular vein Jugular pressure then fell from 37 to 3 mm water Obviously up to this degree of suction flow increased *proportionally to the pressure gradient* without the intervention of collapse With greater degrees of suction, blood flow failed to increase further and in fact decreased slightly This is illustrated by the leveling and decline of the flow curve in Fig 25 The fall of jugular venous pressure to zero indicates that outflow is limited by the advent of a partial collapse when the extravascular pressure (atmospheric pressure) and intravascular pressure (zero right limb of curve C) reach an equilibrium

It is interesting that these pressure flow relations which exist in the veins of *living* organisms (curve A Fig 25) have been established by Holt (1941) in experiments with physical models using collapsible rubber tubes and excised veins

From the flow records in Fig 24 and flow pressure relations plotted in Fig 25 one must conclude that venous collapse does not occur instantaneously when the pressure in a downstream portion of the vessel is suddenly lowered Collapse is actually a two stage process The first is called the *depleting stage* (steep flow increase in Fig 24E) During this stage the transmural venous pressure declines

and the vein empties most of its blood into the region of the lower pressure This is followed by the *collapsed stage* of the vein which is reached after its depletion has been accomplished (sudden flow reduction in Fig 24E)

From the data shown in Fig 24 it is now possible to calculate in absolute

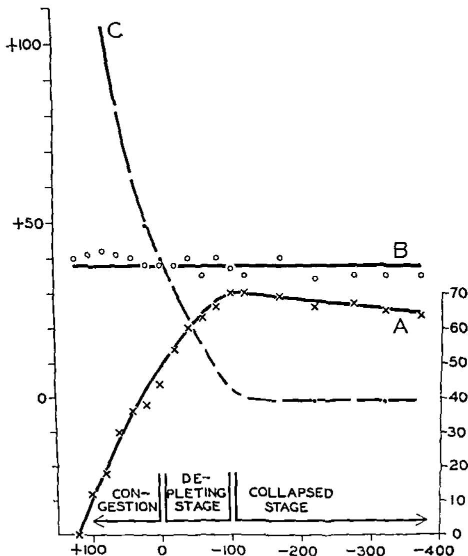


FIGURE 25 Relation of flow and pressures in a collapsible system Curve A Flow pressure relation to drainage from the superior vena cava tree Curve B Control jugular pressure before the 10 sec periods of flow measurement Curve C Maximal rise (left limb) or fall (right limb) of jugular venous pressure during flow measurement Note that in the collapsed stage of the venous tree the pressure in the jugular vein never falls below zero i.e. atmospheric pressure Ordinate for curve A (right) cc of vena caval blood drained in 10 sec Ordinate for curves B and C (left) mm water Abscissa for all curves height of outflow level above or below the level of the jugular vein in mm water

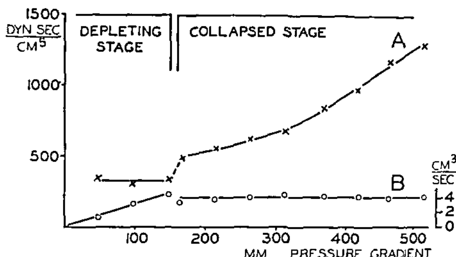


FIGURE 26 Relation of resistance flow and pressure in a *collapsible vein* of a *living* dog The data show the relation of resistance (curve A) to volume flow (curve B) during the depleting and the collapsed stages of the superior vena cava system when different degrees of suction are applied to the end of the outflow drainage tube of the superior caval vein Ordinate for curve A (left) resistance in dyne sec/cm Ordinate for curve B (right) Flow in cc per sec Abscissa for both curves pressure gradient between jugular vein and height of outflow level in mm water

unit the resistance in the veins at different degrees of suction using the formula

$$Q = \frac{p_1 - p_2}{R}$$

The results are graphically represented in Fig 26 Curve A shows that the resistance did not change appreciably while outflow from the vein (curve B) increased upon moderate suction such as one can observe during the depleting stage However as soon as the collapsed stage of the vein was reached resistance to flow increased progressively with greater degrees of suction Attention is called to the sudden break in the course of the two curves which clearly illustrates the different behavior of the veins in the two stages

The experiments in living animals revealed the importance of the time factor for the development of collapse as manifested by the existence of the depleting stage It was of interest to see whether the depleting stage was also reproducible in physical analogue Collapsible rubber tubing was used to represent a vein Flow was recorded in a manner corresponding to that in the animal experiments Figure 27 illustrates the flow pressure resistance relation in a collapsible rubber tube In the rubber segment undergoing depletion resistance to flow remained nearly constant (horizontal part of curve A) whereas flow varied linearly with the pressure gradient (ascending limb of curve B) However, as soon as the suction was increased sufficiently to cause the rubber tube to enter the collapsed stage (at about −70 mm suction) resistance increased progressively (ascending limb of curve A) whereas flow remained constant (horizontal part of curve B)

Comparison of the pressure flow resistance relationship in Figs 26 and 27

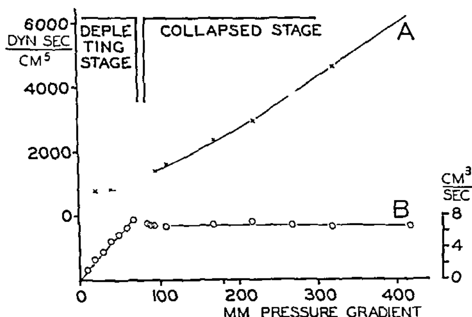


FIGURE 27 Relation of resistance flow and pressure in a collapsible rubber tube which is arranged in a *physical model* so that it corresponds to a vein in a living animal Plotting and labeling are the same as in Fig 26 except that a collapsible rubber tube replaces the superior vena cava

reveals a remarkable similarity of flow behavior of veins in situ and of the collapsible tube of the physical model This emphasizes the purely physical nature of hemodynamic events in venous collapse

Summarizing

Increase in the pressure gradient along a collapsible vein by the application of suction at one end results first in the emptying of the vessel (depleting stage) before it enters the collapsed stage During the depleting stage outflow from the vein varies in proportion to the pressure gradient and resistance to flow remains approximately constant During the collapsed stage outflow from the vein remains approximately constant while the resistance becomes greater with an increase in pressure gradient

Significance of Venous Collapse in the Peripheral Circulation

The fundamental flow dynamics in collapsible structures may help to explain venous flow in various physiological conditions Some of these considerations are not based on direct experimental evidence and require further experimentation

Locally developed flow pulsations as shown in records D E and F of Fig 24 are not necessarily characteristic of venous behavior in the collapsed stage The pulsation is caused by a momentary complete collapse of a venous segment in which intraluminar pressure is exceeded by extraluminar pressure The blood

which continues to flow from the capillaries into the peripheral portion of the vein forces the closed segment to open again

The following complex relations of frequency and amplitude of the pulsations were found in living animals and physical analogues (Brecher, 1952) The frequency became higher with (1) increasing rigidity of the vessel wall and surrounding tissues (2) a decrease of volume flow through the vessel and (3) greater suction The amplitude became greater with (1) a decrease in frequency (2) greater volume flow and (3) less suction Pulsatile flow is often reflected in oscillations of venous pressure not related to the heart rate Pulsations of a frequency as low as 1 per 20 seconds and as high as a few hundred per second could be produced in suitable analogues In animals we have recorded pulsations ranging in frequency from 3 to 20 per second

Pulsations in collapsed veins do not occur so often under physiological conditions as they do in experimental systems where a collapsible tube is expanded by a rigid outflow cannula Under normal conditions, in man and animals, pulsations can be occasionally observed at places where a collapsible vein enters a low pressure region through tissues which tend to keep the vein open such as the entry of the thoracic cage

On the basis of this knowledge an explanation can now be advanced for the behavior of jugular venous flow which Barry (1824) observed in a standing horse (p 9) Obviously flow through the glass bulb cannula inserted into the jugular vein can not be augmented by inspiration because under Barry's particular experimental condition (collapsed stage of vein) flow would not increase with greater suction (right limb of curve A in Fig 24) The pulsatile flow in the glass bulb was merely the result of local pulsatile collapse of the vein independent from the heart action (compare Fig 24)

Many veins are anatomically so situated that they collapse easily when the extravascular pressure exceeds the intravascular pressure For surface veins the most important extravascular pressure which leads to collapse is the atmospheric pressure in deeper veins it is the surrounding tissue pressure acting on the venous walls

However it must be borne in mind that not all veins are collapsible This applies particularly to the venous sinuses which upon suction are held open by the *counterforce* of firm walled tissues such as exist in the skull bones liver and spleen As long as the volume of cerebrospinal fluid remains constant the venous plexuses extending the whole length of the spinal column and the intervertebral veins serve as an incollapsible communication system for the return flow of blood Via capillaries and venous sinuses in the skull these veins form a communicating system with the arteries corresponding to an inverted U tube in a person sitting or standing up Flow through this U tube system would not be much affected by positional changes (see also Fig 3A) Owing to this rigid communicating system *sub*atmospheric pressures can develop in the cerebral sinuses during head to foot (positive) acceleration on a centrifuge without much impairment of the cerebral circulation (Rushmer et al 1947)

One may therefore state that venous return in head, neck and trunk occurs over two principal routes through the incollapsible skull and vertebral channels and through collapsible veins Both systems communicate at all levels Little

is known about the flow interrelations of the two routes It appears that, re gardless of positional changes flow from the head remains relatively constant owing to the flow dynamics peculiar to each system That is flow through the rigid vertebral system does not change by virtue of the U shaped communica tion with the thick walled arteries (see Fig 3A) and flow in the collapsible system remains constant due to the resistance changes in the partially col lapsed veins (see behavior of flow and resistance in the collapsed stage Fig 26)

Parenthetically it should be mentioned that the giraffe and the human being do not differ essentially in their problems of cerebral blood supply This subject has always fascinated physiologists and laymen as shown by the wide interest given the attempt at measuring the giraffe s blood pressure by Goetz and Budtz Olsen (1955) and Goetz (1955a b) Flow to and from the giraffe s head in the erect position appears to be assured by the siphoning action of the rigid com munication system of arteries and intervertebral venous channels Even if the pressure in the cerebral sinus were subatmospheric return flow through other venous channels would be automatically regulated by the collapse mechanism With the giraffe s head lowered the rigid siphoning system would not es sentially change However when the head is lowered the collapsible neck veins would become greatly distended by a high hydrostatic blood column This is apparently prevented by breaking up the high column into small segments since the jugular vein of the giraffe contains numerous valves as Goetz has shown

Summarizing

Pulsatile flow through collapsed veins occurs under certain normal and ex perimental conditions As a local phenomenon it is unrelated to pulses origi nating from the heart Venous return in head neck and trunk occurs via two routes (a) through a system of collapsible veins and (b) through a system of incollapsible veins in the cranium and vertebral column The latter acts to gether with the arteries as a siphon through which blood flow becomes rather independent of changes in position

The Muscle Pump Without Valves

The effects of contraction of voluntary muscles on venous return have been amply studied and reviewed (Ledderhose 1906 Jager 1937 Franklin 1937 Burch 1950) One may conclude that provided all other factors (arterial per fusion pressure etc) remain the same venous return is increased by the me chanical action of muscular contraction in the veins

The presence of venous valves has often been considered as being of prime importance in assuring effective movement of blood toward the heart during the milking action of the muscle pump However anatomical valves may not be essential for this Alexander (1951) stated concisely the basic issue Extra vascular compression of a vessel will result in an equivalent flow of blood in both directions from the point of compression only under the conditions that the re sistance to flow in both directions is the same If there is a difference in the re sistance in the two alternate directions then greater flow will occur preferentially toward the end of least resistance Even in the complete absence of ana

tomical valves the vessels towards the capillary end of the venous system together with the continuous arterial inflow should always represent a significantly greater resistance than that found in the vessels towards the heart together with the cardiac outflow In view of this relationship rhythmical compression of any vein should aid in propelling blood back towards the heart' For clarification it may be added that these considerations do not conflict with the fact that the essential function of the venous valves is to prevent over distension of the venous walls in the dependent parts of the body (see page 19)

The physiological and pathological importance of this problem need not be amplified Many veins do not contain valves, e g veins within the muscles The valves are located at the exit of the vein from the muscle In advanced age and under pathological condition valves may become incompetent or disappear Nevertheless it is often observed clinically that even in the absence of valve venous return improves during periods of rhythmical muscle movement In connection with the studies on venous collapse our laboratory group became interested in the search for a mechanism which could promote venous return through valveless veins (Brecher et al 1952)

In order to accomplish this all factors which in an experiment could alter venous flow such as change of arterial inflow humoral metabolic and nervous influences had to remain constant Thus the problem became a purely mechanical one which can be stated in its basic form Does rapid rhythmical compression (collapse) of a vein augment the rate of volume flow through it?

As far as the mechanism is concerned it is immaterial what extravascular force causes the collapse of the vein (e g compression by air or muscle ligament joint bone etc) For experimental purposes venous collapse was brought about by atmospheric pressure when suction was applied to a venous outflow tube using an arrangement similar to the one illustrated in Fig 23 It was determined whether or not frequently repeated depletion and refilling of the veins by rapidly alternating pressure gradients results in a *net* increase of flow over that obtained when the same pressure gradients are less frequently acting Under these strictly controlled conditions all factors remained the same except for one variable the frequency with which veins were compressed The experiments in living animals were duplicated by physical analogues in which collapsible rubber tubes were used instead of veins

In Fig 28 four records are shown demonstrating the effect of the alternation between two pressure gradients on volume flow through collapsible structures during a 12 second flow period Records A and B are from experiments on a physical model using rubber tubing records C and D are from a dog In the records on the left side the steeper of the two pressure gradients (350 mm water) acted for 6 seconds bringing about depletion and partial collapse (X to Y) This was followed by the smaller pressure (40 mm water) acting for 6 seconds (Y to Z) which resulted in outflow without collapse of vein or rubber tubing On the right side outflow and pressures were recorded when the same two pressure gradients (X to Y and Y to Z) were alternated every two seconds

In the physical model, flow was increased from 103 to 115 cc (11 6 per cent) simply by alternating the two pressure gradients every two seconds In the corresponding dog experiment venous drainage from the superior vena cava was

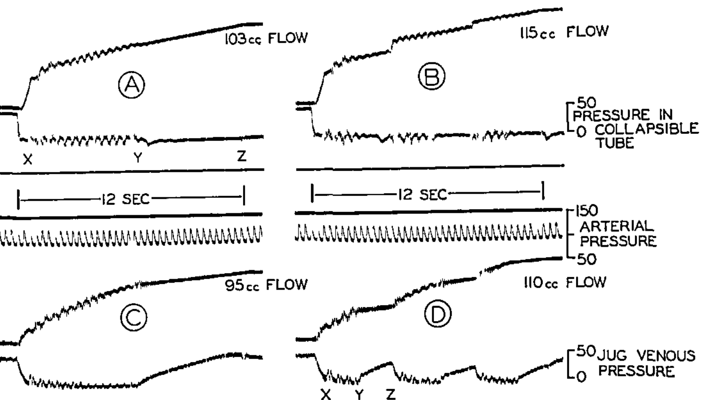


FIGURE 28 Illustration of a net flow increase by the frequent alternation of pressure gradients in veins or collapsible tubes A and B = records from physical models Tracings from top to bottom *cumulative flow pressure in collapsible tube* base line C and D = records from dog Tracings from top to bottom base line femoral artery pressure cumulative flow jugular vein pressure at junction of external maxillary and facial vein

increased from 95 to 110 cc (15 7 per cent) by the same maneuver This experiment could be continued for much longer periods than 12 seconds

The net increase of total flow by the frequent alternation of the pressure gradients is due to the fact that in the collapsible structure a reserve of fluid accumulates during each incidence of the smaller pressure gradient (muscle relaxation) Then *since resistance to flow in the collapsible segment is still low during the depleting stage,* a large volume flow occurs when the vein begins to empty under the influence of the high pressure gradient (muscle contraction) As soon as it is emptied and the collapsed stage is reached, resistance rises sharply and the flow rate drops A simple calculation from the records in Fig 27 shows that the mean resistance in the venous tree was decreased during the 12 second flow period from 2414 to 2082 dynes sec/cm^5 (13 8 per cent) merely by alternating the pressure gradient more frequently

The implications of these experiments are obvious They establish the existence of a simple physical mechanism by which one can explain an augmentation of venous return in valvele ss vessels through rapid rhythmically alternating movements such as occurs in walking running exercising etc

Summarizing

Rapidly alternating compressions of collapsible valveless veins increase flow compared with that occurring with less frequent compressions

VII The Respiratory Pump

An understanding of the collapse mechanism has greatly aided in approaching the cardinal question Does inspiration augment venous return or not? (See pages 8 and 27)

TIME FACTOR IN VENOUS COLLAPSE

In the outflow experiments shown in Fig 24 the sudden suction exerted on the superior vena cava would physically correspond to the suction on the extra thoracic veins exerted by an inspiration in an organism with the chest closed *It should be noted that the collapse of the veins by suction does not occur* instantaneously with the onset of aspiration The records in Fig 24 illustrate that collapse is not only a function of the magnitude of the pressure gradient (suction) but also of the time over which it acts This is graphically represented *in Fig 29 by plotting the time it takes the veins to become depleted against* the degree of suction (pressure gradient) The data are taken from the records in Fig 24 and other records from the same experiment According to these measurements the duration of the depleting stage lasted 3 5 seconds at a suction *of 150 mm water At greater aspiration this time became progressively shorter*

From the findings in the strictly controlled open chest experiments one can *predict* the effect of inspiration on venous return in the closed chest Under physiological conditions in the recumbent position with the venous bed at the *hydrostatic level of the heart quiet inspiration may merely be expected to* deplete the peripheral veins without inducing their collapsed stage The suction would be too little and the time over which it acts too short to collapse the extrathoracic veins For illustration a typical intrathoracic pressure curve (Fig 29 curve B) *of a quiet spontaneous respiration is entered on the graph* Only forced deep inspirations would produce negative pressures of sufficient magnitude and duration to bring about the collapsed stage This is illustrated by the intrathoracic pressure curve (Fig 29C) of a forced inspiration (Muller s experiment) The next step is to prove that this is the case

Summarizing

From venous drainage experiments it is predicted that inspiration should augment venous return by depleting the blood from the extrathoracic veins into the thoracic veins During quiet inspiration in the recumbent position the extra thoracic veins should not collapse to such an extent as to throttle venous re turn During deep and prolonged inspiration the extrathoracic veins should after their depletion enter the collapsed stage and prevent a further aug mentation of venous return

EFFECT OF RESPIRATORY MOVEMENTS ON SUPERIOR CAVAL FLOW

In this experiment a Pitotmeter (Fig 11B) was inserted into the *superior vena cava* of a supine dog Then the chest was closed and normal intrathoracic

pressures were re established (Brecher and Mixter, 1953) In contrast to the cumulative (slope) records shown in Figs 21 and 28 this device indicated the *rate* of volume flow (see page 30) Figure 30 shows a segment of an original record illustrating the effect of normal quiet breathing on venous return Flow measured at comparable phases of the cardiac cycle, increased from 5 2 cc/sec during the respiratory pause to 11 cc/sec during inspiration Right atrial pressure declined in the usual manner with the lowering of intrathoracic pressure Jugular pressure measured 7 cm cephalad to the first rib, fell from 35 mm water to zero From these findings one must conclude that venous return increases significantly with inspiration

Examination of the flow tracing in Fig 30 reveals that during quiet inspiration inflow into the right heart, as predicted is not throttled by a collapse of the veins at their entry into the chest To see whether a deep and long inspiration would bring about the collapsed stage in the predicted manner, flow was measured during partial occlusion of the trachea during the very next inspiration following the quiet inspiration shown in Fig 30 The flow occurring during this forced inspiratory attempt is illustrated in Fig 31 Here again inflow increased immediately at the onset of inspiration In fact it increased more rapidly and to a greater extent (13 5 cc/sec) as the fall of intrathoracic pressure developed more rapidly and to a greater depth than during quiet inspiration However after 1 to 2 seconds flow diminished in spite of continued inspiration The decrease in flow occurred although right atrial pressure declined further and the pressure gradient from the jugular vein to the right atrium became greater

Obviously a resistance to flow developed between the two points of pressure measurement (jugular vein and right atrium) because the extrathoracic veins entered the collapsed stage Evidence for the occurrence of a partial collapse of the extrathoracic veins near the entry of the chest is seen in the course of the jugular venous pressure It began to fall with the onset of inspiration and finally reached zero but did not develop a negative pressure Then shortly after having reached zero it began to rise again although the thoracic aspiration was still increasing This peripheral venous pressure rise must be caused by the combined action of a high resistance in the partially collapsed venous segment near the entry into the thoracic cage and the continued inflow of blood from the capillaries Since the jugular pressure rise from zero commences simultaneously with the end of further increase of flow the correlation of pressure flow and resistance in the collapsed stage becomes very apparent It is basically of the same nature as that produced under the strictly controlled conditions in which venous collapse had been studied previously

The correlation of the pressure and flow tracings in Fig 31 demonstrates that *in the venous system flow does not necessarily increase proportionally to an increase in the pressure gradient*

From these experiments it becomes apparent that the two controversial views the classical "aspiration" and the "collapse" theory of venous return do not conflict but actually complement one another Venous collapse during inspiration does not occur instantaneously but is a two stage process During the first

stage the *depleting* stage, the demands of the classical theory are satisfied venous return to the heart varies in direct proportion to the pressure gradient During the second stage the collapsed stage the collapse theory of Holt and Duomarco is applicable venous return is not augmented because resistance increases with greater pressure gradients Previous failure to recognize this situation must be ascribed to the fact that only the simultaneous direct recording of phasic changes in flow and pressure with instruments of adequate sensitivity and frequency response could furnish the necessary information

It remains to be demonstrated that the augmentation of venous return during inspiration is not cancelled by a corresponding flow reduction during expiration or in other words that the respiratory pump provides a net gain of

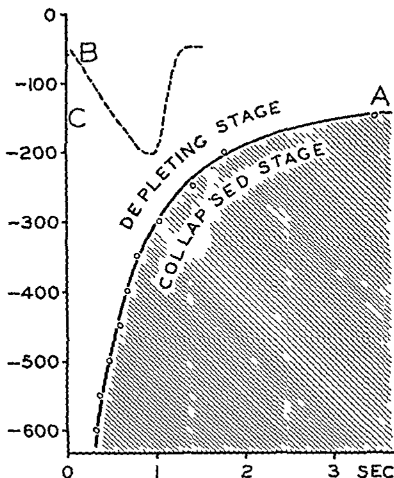
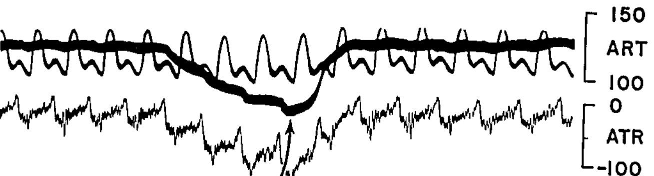


FIGURE 29 Relation of the duration of the depleting and onset of the collapsed stage to the degree of suction applied to the superior vena caval system Curve A duration of venous depleting stage at different degrees of aspiration Curve B typical intrathoracic pressure during quiet respiration Curve C typical intrathoracic pressure during Müller's experiment Ordinate negative pressure in mm water



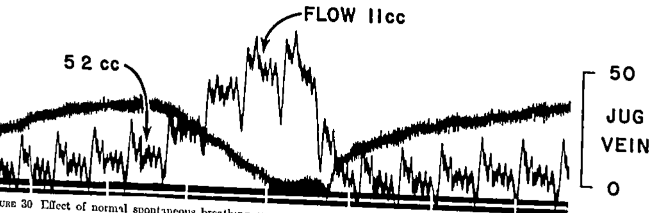


FIGURE 30 Effect of normal spontaneous breathing on venous return in the closed chest Tracings from top to bottom intrathoracic femoral arterial right atrial and jugular vein pressures flow in superior vena cava base lines Pressures are in mm water except for arterial pressures which are in mm Hg volume flow in cc/sec time in seconds

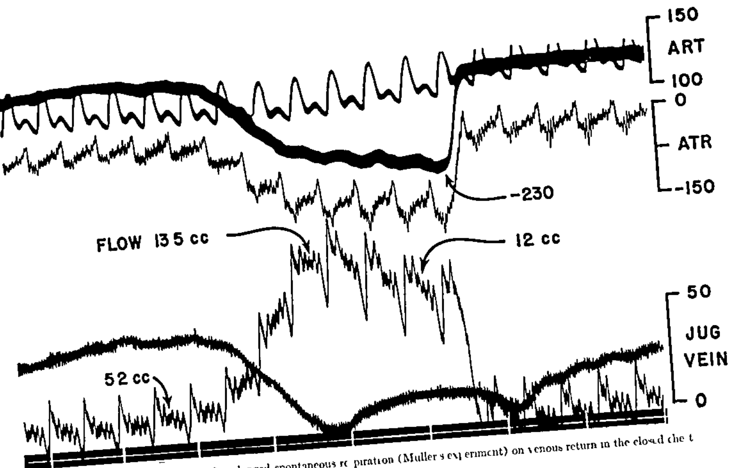


FIGURE 31 Effect of deep and prolonged spontaneous respiration (Muller's experiment) on venous return in the closed chest Tracings as in Figure 30

venous return This problem has long been known Volkmann (1850) mentioned that if inspiration did increase venous return expiration might decrease it by the same amount Examination of the records in Fig 30 and 31 reveals that venous return is slightly reduced upon expiration since the pressure gradient is less and the blood reservoir in the extrathoracic veins requires time for replenishment However, the "expirogenic" flow reduction is not so great as the "inspirogenic" augmentation As a result there is a net gain of return flow of blood to the heart by the action of respiration The physical principle of the underlying mechanism which increases the net venous return by the rhythmical action of respiration is in essence the same as that illustrated in Fig 28 In those experiments it was demonstrated by direct measurements that rhythmical depleting and refilling of the peripheral veins may increase net venous return

Eckstein et al (1947) observed in dogs with *open* chest an increase of *inferior vena cava* flow when the diaphragm muscle contracted Such flow augmentation was obviously not caused by thoracic aspiration but by squeezing out of blood from the abdominal inferior caval tree To determine whether contractions of respiratory muscles affect flow also in the *superior* vena caval tributaries we measured superior caval flow in the open chest This was done in order to establish whether the respiratory flow increase shown in Figs 30 and 31 is actually due to thoracic aspiration (suction) or to a squeezing out of blood from extrathoracic veins solely by respiratory muscle contractions (Brecher and Mixter 1953) The record depicted in Fig 32 was taken when artificial respiration was discontinued for a brief period and spontaneous respiratory movements reappeared Onset and duration of a forceful inspiratory attempt is indicated by the tracing from a pneumograph placed around the open chest The flow tracing remained essentially unchanged during apnea and during the inspiratory effort From this experiment it can be concluded that the contractions of the respiratory muscles *per se* do not augment flow in the superior caval system The increase of *superior* caval venous return in the closed chest must therefore be attributed to thoracic aspiration

Summarizing

In the closed chest spontaneous respiration augments venous return in the superior vena cava The increase is caused by emptying of blood from the extrathoracic veins (depleting stage) into the thoracic veins After their emptying the extrathoracic veins enter the collapsed stage if the inspiration is deep and long In the absence of thoracic aspiration (open chest) superior caval flow remains constant when respiratory muscles contract

Influence of Respiration on Inferior Caval Flow

The situation in the inferior vena cava is more complex than in the superior caval tree Whereas the superior caval system traverses essentially two compartments of changing pressures (thoracic and extrathoracic areas), part of the inferior cava drains through three compartments (thoracic abdominal and extra abdominal areas) In the inferior caval system pressures may vary independently according to various activities of the body For example, during

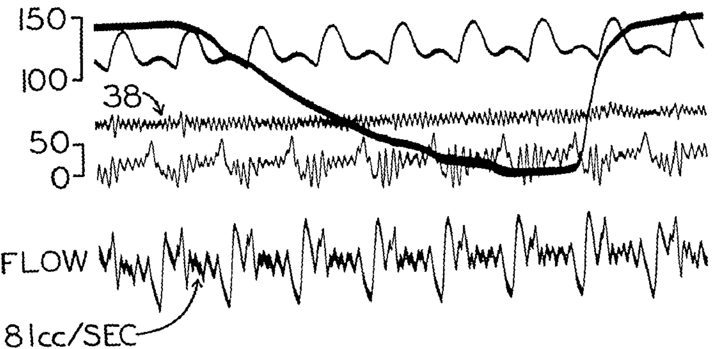


FIGURE 3 Effect of respiratory muscle contraction on [illegible] jugular vein and right atrial pressure, flow in [illegible] superior vena [illegible] vena cava flow in the open chest. Tracings from top to [illegible] Time 4 seconds ([illegible] segment of record) bottom pneumograph femoral artery pressure in mm Hg

spontaneous inspiration intrathoracic pressure declines intra abdominal pressures rise, and the tissue pressure level in the legs remains unchanged Special anatomical structures such as the caval band' at the level of the diaphragm (described and emphasized by Franklin and Janker, 1934, 1936) may hinder flow from the abdominal to the thoracic inferior cava during inspiration For an understanding of the over all behavior it is therefore necessary to consider the various factors aside from thoracic aspiration which are operative in determining return flow in the inferior vena cava This was done by Mixter (1953) in our laboratory

With two Pitotmeters (Fig 11B) Mixter directly compared flows in the thoracic and the abdominal portions of the inferior vena cava the latter being measured below the renal veins Fig 33 shows a section of flow and pressure tracings taken during natural respiration of a closed chest dog The flow curves from both the thoracic (VC 1) and the abdominal (VC-2) portion of the caval vein show cardiac variations details of which will be considered later Thoracic

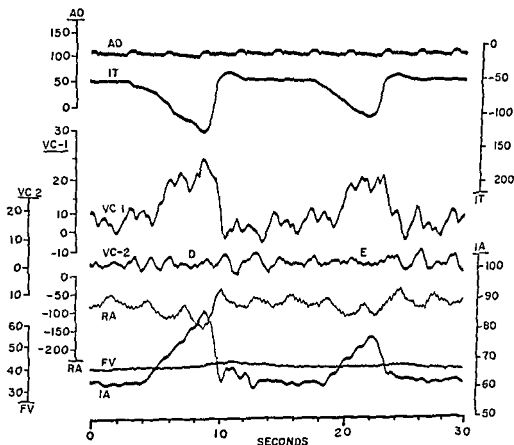


FIGURE 33 Effect of natural breathing on flow in the thoracic and abdominal inferior vena cava Tracings from top to bottom aortic pressure (AO) in mm Hg intrathoracic pressure (IT) in mm water thoracic inferior cava blood flow (VC 1) in cc/cc abdominal inferior vena cava blood flow (VC 2) in cc/sec right atrial pressure (RA) femoral vein pressure (FV) and intra abdominal pressure in mm water Time in seconds (After Mixter 1953 modified from original)

flow increased during inspiration with retention of the cardiac variations but the general flow level changed much less in the abdominal cava and the cardiac variations became almost obliterated as at D and E The latter phenomenon ocurring synchronously with the leveling off of the rising thoracic flow curve appeared to be caused by the onset of the collapsed stage analogous to that described in the superior caval system It is further noted that with the descent of intrathoracic and right atrial pressure intra abdominal pressure rose This in itself would aid in the emptying and collapse of the abdominal vena cava Femoral venous pressure rose slightly during the deeper (first) inspiration apparently owing to the resistance increase in the partially collapsed inferior cava

In order to eliminate the contribution of the diaphragmatic contraction to the inspiratory flow increase and to see whether thoracic *suction alone* would augment inferior caval flow Mixter quickly cut both phrenic nerves in the closed chest while taking a continuous record Figure 34A shows a segment of the record during spontaneous quiet breathing illustrating the concerted action of intercostal and diaphragmatic muscles Segment B was taken briefly after the phrenicotomy, when respiration was maintained by the intercostal muscles only Segment A shows an increase of thoracic inferior caval flow at the beginning of inspiration then a leveling off when the collapsed stage was reached Abdominal caval flow diminished throughout the inspiration This diminution was caused by the partial collapse of the vein due to the abdominal pressure rise The partial collapse of the abdominal cava leads in turn to a slight rise of femoral venous pressure After phrenicotomy (B) intra abdominal pressure (GA) fell during inspiration femoral venous pressure (FV) declined slightly abdominal caval flow increased slightly but distinctly and intrathoracic caval flow increased throughout inspiration The average thoracic inferior caval flows before and after phrenicotomy were not significantly different

These experiments demonstrate (1) that thoracic suction alone can augment inferior caval flow and (2) that the diaphragmatic contraction squeezes blood from the abdominal cava but in doing so enhances the partial collapse of the abdominal cava when it is compressed by the abdominal contents These findings do not support the idea of a diaphragmatic sphincter advanced by Franklin and Janker (1934 1936) and Franklin (1937) Such a sphincter would prevent the inspiratory flow augmentation

The various factors affecting flow through the inferior caval system during different types of respiration are quantitatively represented in Fig 35 (Mixter 1953) For better visualization the flow during each cardiac cycle was integrated and then plotted In each plot the upper curve represents flow in the thoracic cava and the lower curve shows the flow in the abdominal cava below the renal veins It should be apparent that the thoracic flow is greater than the abdominal flow by the amount contributed from the renal and portal outflows The dotted lines symbolize mean flows throughout the respiratory cycle

For comparison thoracic caval mean flow was maintained in all respiratory conditions at about the same level through judicious blood infusion The flow data in Fig 35A show the constancy of flow during *apnea vera* in the open chest

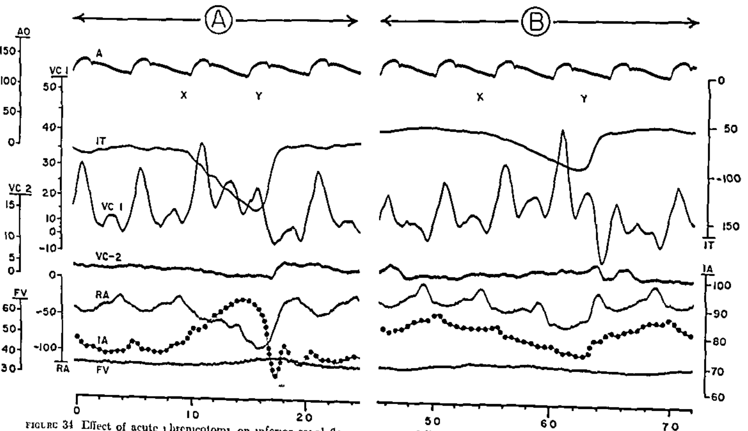


FIGURE 34 Effect of acute phrenicotomy on inferior caval flow in the closed chest. Tracings in segment A, phrenic nerves intact. Segment B, 1 minute after nerve section. Note persistence of centripetal acceleration (VC 1) even though abdominal pressure falls during inspiration. Abdominal flows (VC 2) are now accelerated during this phase rather than retarded (compare with A). (After Mixter 1953, modified from original.)

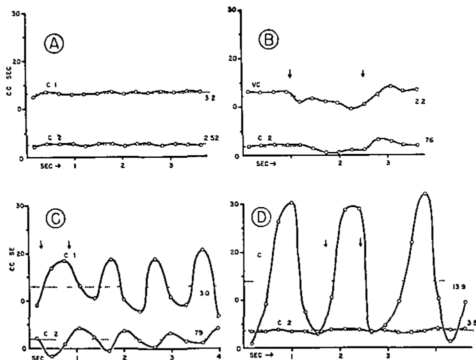


FIGURE 35 Flow through the inferior caval system as influenced by certain respiratory components Solid lines mean flow per cardiac cycle through thoracic cava (VC 1) and abdominal cava (VC 2) Dotted lines mean over all flow during period analyzed X and Y = onset and cessation respectively of inspiratory phase of respiration A = flow during hyperventilation apnea chest open B = depression of flow during positive pressure inflation of lungs chest open C = effects of diaphragm descent chest open D = flow behavior after chest closed Figures at right hand end of charts refer to values for over all mean flow in cc/sec (After Mixter 195)

In 35B a positive pressure lung inflation beginning at X and ending at Y resulted in a flow reduction in both portions of the cava In 35C the effect of respiratory attempts in the open chest is visualized Intra abdominal pressure began to rise at X (onset of inspiratory effort) leading to a thoracic caval flow increase and an abdominal caval flow decrease The reverse took place when it began to fall at Y (end of inspiratory effort) In 35D the chest was closed X and Y denoting the onset and cessation of spontaneous inspiration respectively Thoracic caval flow was greatly increased during inspiration and depressed during expiration whereas abdominal caval flow became practically constant

This shows that flow through the abdominal cava is most efficiently maintained by the combined action of thoracic suction and abdominal compression which balance one another rather delicately Of the four respiratory conditions shown in Figure 35 mean flow in the abdominal cava was greatest in the closed chest (35D)

All studies on venous collapse mentioned so far were undertaken on animals with normal blood volume However one could well imagine that the depleting



FIGURE 36 Effect of venous plethora upon inspiratory augmentation of thoracic inferior caval flow Abscissa time in seconds Ordinate blood flow in cc/sec Animal progressively transfused between curve A (mean blood pressure 78 mm Hg) and curve D (mean blood pressure 122 mm Hg) All respiratory cycles of same length Note progressively higher basal levels progressively greater maximal flows and progressively prolonged increase of volume flow during inspiration (w x y and z) (After Mixter 1953)

stage would be shortened in a hypovolemic animal whose extrathoracic venous reservoir would be quickly emptied with the onset of thoracic aspiration The modifications of inferior caval flow by hypovolemia and hypervolemia were studied by Mixter (1953) during spontaneous respiration in the closed chest Figure 36 is a composite graph of inferior caval flows taken during four respiratory cycles of the same length and depth in the same dog Between the first respiratory cycle (A) and the last one (B) the animal was transfused until the mean arterial pressure rose from 78 to 122 mm Hg While the basal flow during the expiratory pause became somewhat greater with increasing plethora of the cava the most striking feature was the progressive increase in the maximal flows induced by inspiration and the concomitant prolongation of the 'depleting stage before the onset of the collapsed stage (W X Y and Z) was reached

Summarizing

In inspiration causes a significant augmentation of venous return via the inferior vena cava Two forces are commonly involved abdominal compression and thoracic suction These forces ordinarily supplement one another but either one is capable of acting separately The forces governing extrathoracic venous collapse obtain also in the inferior cava The elevation of abdominal pressure enhances the tendency toward collapse

Respiratory Variations of Portal Flow

It has been suggested that among the abdominal organs the liver may contribute specifically to an augmentation of inferior caval flow during inspiration (For review see Gollwitzer Meier 1932) By measuring drainage from the portal vein through an outflow cannula Alexander (1951) demonstrated that the contracting diaphragm compresses the hepatic and splanchnic beds and may thereby increase venous return When he used the drainage method the resistance of outflow from the portal bed remained constant because the outflow cannula was set at a fixed level during the flow determinations However such a situation may not prevail when the portal circulation remains uninterrupted between the splanchnic area and the liver vascular bed With the continuous circulation the resistance to flow from the portal vein into the liver may be altered when the liver is compressed or shifted by the contraction of the diaphragm

As part of a recent study on liver flow we re examined this problem in our laboratory by inserting directly into the portal vein a bristle flowmeter (Selkurt and Brecher 1956) The flow measurements were undertaken in naturally breathing anesthetized dogs In this experimental arrangement portal flow would be affected not only by a compression of the splanchnic bed but also by resistance changes in the liver bed that might occur during respiratory movements

As illustrated in Fig 37 portal venous flow (second curve from top) decreased slightly but distinctly during inspiration Simultaneously recorded portal

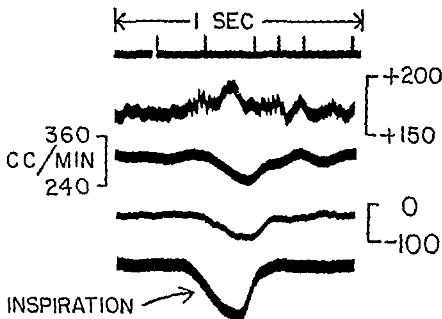


FIGURE 37 Changes of portal venous flow during natural breathing Tracings from top to bottom portal venous pressure in mm water blood flow in portal vein in cc/min hepatic venous pressure in mm water intrathoracic pressure during one respiratory cycle (Unpublished record of Selkurt and Brecher)

venous pressure rose, whereas hepatic venous pressure declined with the greater negativity of the intrathoracic pressure This pattern of portal flow behavior was general in these experiments

Although it may seem otherwise at first glance, these results do not conflict with the previous findings of Alexander (1951) The diminishing of portal flow in our experiments evidently resulted from an increase in resistance to blood flow through the liver bed when this organ was compressed by the descent of the diaphragm This explanation is supported by the fact that the pressure gradient along the vascular bed of the liver from the portal to the hepatic vein became greater during inspiration

Thus it appears that inspiration has a dual effect on portal venous flow dynamics By compressing the splanchnic bed flow toward the liver is augmented (Alexander 1951) However owing to a concomitant increase of resistance in the liver bed thus increased volume flow is not passed on to the liver veins Instead it leads to a slight pooling in the portal vein where flow is slowed down during inspiration The pooled portal venous blood would then be available for filling of the vascular bed of the liver during expiration On the other hand it appears safe to assume that the compression of the liver during inspiration results in a simultaneous emptying of the hepatic venous channels toward the inferior vena cava

Summarizing

Flow in the portal vein decreases slightly during inspiration owing to a resistance increase in the vascular bed of the liver However hepatic venous flow may increase during inspiration

Respirogenic Changes of Total Venous Return

After a separate treatment of each vena cava system it appeared necessary to establish the synchronicity and interrelation of the flow events in both vessels Flow was simultaneously measured in the *superior* and *inferior vena cava* with two Pitotmeters (Brecher and Mixter 1952) or two bristle flowmeters (Hubay and Brecher unpublished) The results are shown in Fig 38 Both segments were taken from the same record

The tracings in the left segment of Figure 38 were recorded during spontaneous respiration with the chest closed It is noted that flow increased and decreased synchronously in both cavae during the cardiac and respiratory cycle Intra abdominal pressure (dotted in the record) and femoral pressure rose during each inspiration In the left segment flows and pressures were recorded 17 seconds later after a quick thoracotomy when the animal made respiratory efforts The strong diaphragmatic contractions produced higher intra abdominal and femoral pressures In the absence of thoracic suction, inferior caval flow was distinctly elevated as a result of the squeezing out of blood from the abdominal inferior caval tree (see also Eckstein et al, 1947) Superior caval flow was practically unchanged These findings tie together the individual observations shown in Figs 30 to 34 Thus under natural conditions thoracic aspiration affects venous return from the upper and lower parts of the body in like manner and leads to an augmentation of right atrial inflow via both caval veins

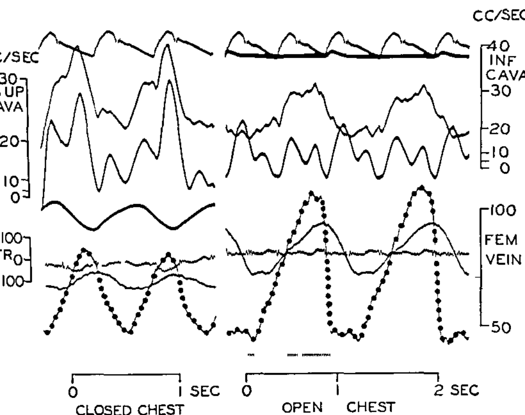


FIGURE 38 Effect of respiration on total venous return measured simultaneously in the superior and inferior vena cava Left segment Spontaneous respiration with chest closed Right segment Respiratory movements during open thoracotomy Tracings from top to bottom aortic pressure thoracic inferior caval flow in cc/sec superior caval flow in cc/sec Intrathoracic pressure in left segment forms an undulating line and in right segment (after opening of chest) a straight line as atmospheric zero pressure below the aortic pressure tracings Right atrial pressure femoral venous pressure in mm water Intra abdominal pressure dotted in record for better visualization (Unpublished record of Mixter and Brecher)

Summarizing

Respiration augments synchronously total venous return from both caval veins under normal conditions

Region of Venous Collapse During Inspiration

Even though it has been demonstrated above that collapse does not occur instantaneously at the onset of inspiration and that at least a portion of the extrathoracic venous reservoir is available for depletion into the thoracic veins little is known about the segment of the vein which collapses Specifically it should be determined whether as Duomarco (1944) claims the veins collapse at a sharply demarcated point at the thoracic inlet or whether longer segments of the extrathoracic vessels collapse

Since a partially collapsed portion of a vessel offers an increased resistance

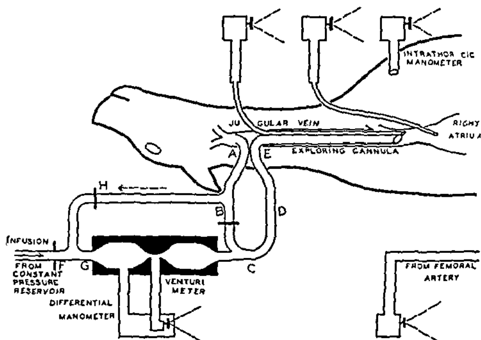


FIGURE 39 Experimental arrangement for studying the regional effects of venous collapse A B C D and E = route of blood flow from external jugular vein to exploring cannula F G C D and E = route of infusion fluid from constant pressure reservoir through venturimeter to exploring cannula Tubing can be clamped at E H or B for various routing of flow Description in text

to inflow this phenomenon was utilized for an exploration of the onset duration and extent of collapse in different regions of extrathoracic veins during normal respiration (Brecher et al 1952) Figure 39 shows a schematic diagram of the experimental arrangement Inflow from a constant pressure reservoir was recorded with a venturimeter via an exploring cannula in the external jugular vein (see Fig 10B)

The three records in Fig 40 illustrate the effect respiration had on inflow when the tip of the exploring cannula was placed in different intra and extrathoracic segments of the superior vena caval system In each record the first inspiration was a normal quiet one and the second was with a partially occluded airway As expected when the tip of the cannula was located in the superior caval vein the flow rate increased proportional to the pressure gradient created by the thoracic suction (Fig 40A) When the tip was placed 3 cm cephalad to the first rib flow increased at the beginning of inspiration indicating that in this *extrathoracic region collapse did not occur immediately* However as soon as the jugular pressure at the cannula tip fell to zero the flow augmentation leveled off indicating the onset of collapse Right atrial pressure declined in the usual manner (Fig 40B) Finally when the tip of the cannula was placed in the jugular vein 11 cm cephalad to the first rib the rate of inflow and jugular pressure remained unaffected by respiration, indicating the interposition of

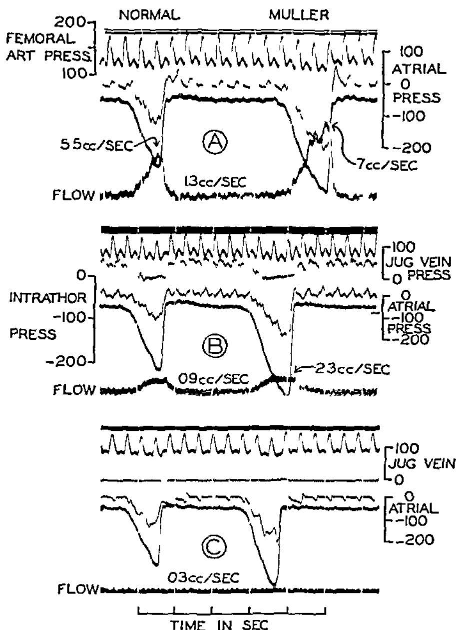


FIGURE 40 Three records illustrating the effect of respiration on the rate of inflow into veins through an exploring cannula. Reservoir pressure 10 mm water in all records. A = tip of cannula in superior vena cava. *B = tip of cannula in jugular vein 3 cm cephalad to the first rib.* C = tip of cannula in jugular vein 11 cm cephalad to the first rib. Tracing in each record from top to bottom: base lines, femoral artery pressures in mm Hg, venous pressures at tip of cannula, right atrial pressures and intrathoracic pressures in mm water, flow through cannula in cc/sec. (Venous pressure tracing omitted in record A.) Description in text.

a collapsed segment of the vein between the cannula tip and the thorax (Fig 40C)

From these findings one may conclude that collapse does not occur at one distinct point at the entry of the thoracic cage but that the collapsing process involves a segment of the extrathoracic vein This segment is a *transition zone*

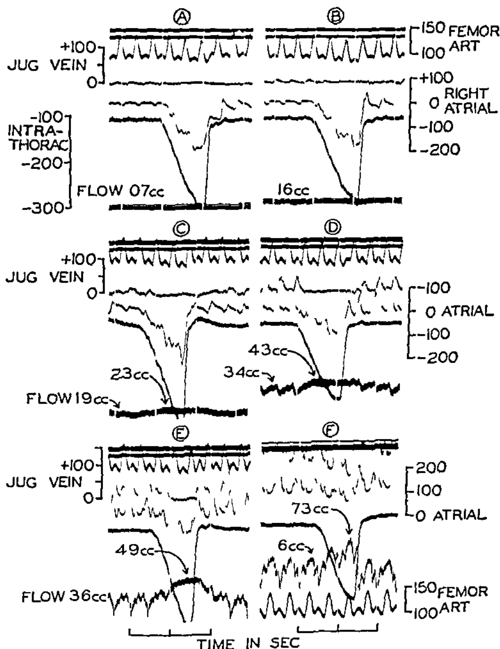


FIGURE 41 Six records illustrating the effect of venous plethora on respiratory augmentation of inflow into the jugular vein Tracings as in figure 40 In record F femoral artery tracing was moved to bottom of record Description in text

between the noncollapsed intrathoracic and the collapsed extrathoracic region of the vein

The extent of the transition zone is of course influenced by various conditions an important factor being the amount of venous filling The six records shown in Fig 41 illustrate the effect of poor venous filling and of venous plethora on the collapse mechanism In all records the tip of the exploring cannula remained stationary in the external jugular vein 11 cm cephalad to the first rib Only the perfusion pressure was increased by stages It is noted that as the vein became more plethoric with greater perfusion pressure the effect of inspiratory suction increased in the peripheral portion of the vein (Fig 41 B through E) The advent of collapse can be deduced from the leveling of the jugular venous pressure curve at zero pressure and the simultaneous plateau of the flow curve Finally when perfusion pressure was highest as shown in Fig 41F collapse was completely abolished

Certain facts are clearly demonstrated by these experiments First inflow into a long segment of a partially collapsed (poorly filled) vein is not affected by inspiration (Fig 41A) Second the transition zone of collapse extends further toward the peripheral region of a vein when the vessel has a normal or greater than normal filling state Thus the extrathoracic vein can accommodate a greater blood volume which is then available for emptying into the thoracic vein during inspiration Third rising right atrial pressure postpones or even prevents collapse In the extreme case represented in Figure 41F this corresponds to the situation existing in congestive heart failure when right atrial pressure does not descend below zero

Summarizing

Upon inspiration the extrathoracic veins do not collapse at a distinct point at the entry of the thoracic cage When intrathoracic pressure declines a transition zone is formed between the noncollapsed intrathoracic and collapsed extrathoracic region of the vein With greater venous plethora the transition zone extends progressively into the peripheral veins

Clinical Inferences

It is now possible to reconcile conflicting reports in the literature on changes of peripheral venous pressure with respiration (Gollwitzer Meier 1932) In human when peripheral flow is normal and the heart well compensated as in the experiments of Lyons Kennedy and Burwell (1938) inspiration is capable of producing significant *decreases* in peripheral venous pressure either momentarily by a deep sighing breath or for prolonged periods by voluntary acceleration of the respiratory rate This clinical observation is explainable on the basis that the depleting stage may be sufficiently prolonged to allow augmentation of return flow by the complete respiratory act When right atrial pressure is low and the onset of inspiration abrupt (Muller s experiment) the peripheral venous pressure decline may not last long and the outstanding feature will be a pressure rise as the venous bed fills up distal to the region of maximal collapse These phenomena are so easily reproducible that they can be shown in student experiments

On the other hand if venous plethora be extreme, as in right heart failure, collapse *cannot* occur and each inspiratory effort is accompanied by a marked increase in volume flow toward the thoracic venae cavae and a clear cut drop in peripheral venous pressure In the absence of collapse in congestive failure each inspiration would tend to increase the inflow load on an already over loaded heart The beneficial effect of morphine in such cases may, in part be explainable by the suppression of respiratory movements

Burch Cohn and Neuman (1942) in simultaneous plethysmographic studies of the finger toe and pinna noted inconstant decreases in vascular volumes in response to spontaneous deep respirations In the light of the above experiments it now becomes clear that the acceleration of venous flow caused by extrathoracic depletion may extend far into peripheral veins the inconstancies observed may in each instance be accounted for by the supervention of collapse in some portion of the extrathoracic venous tree according to the peripheral venous filling status

Summarizing

The clinically observed fall in peripheral venous pressure during quiet inspiration is caused by an emptying of the veins toward the chest The rise of peripheral venous pressure during forced inspiration is caused by a partial collapse of the veins near their entry into the chest In right heart failure venous collapse may not occur and inspiratory efforts will increase the inflow load to the overloaded heart

VIII Effect of Artificial Respiration on Venous Return

With the more extensive use of artificial respiration and controlled mechanical respiration in medical and surgical procedures interest has recently been focused on the effect of respirators on the circulation It is generally agreed that one of the detrimental effects of controlled respiration is the mechanical interference of positive pressure lung inflation with venous return (for reviews see Watrous et al 1951 Whittenberger 1955)

A controversy has existed for many years as to whether or not in the *closed* chest the interposition of negative pressure between the periods of intermittent positive pressure lung inflation can improve the circulation Again as in the case of spontaneous respiration, it has been argued that negative airway pressure could not increase venous return because of venous collapse at the entry of the thoracic cage (Holt 1943) Some data suggest that alternating positive negative pressure respiration may benefit the circulation (Rost 1932 Kemph et al 1952 Maloney and Handford 1954 Anschutz et al 1955) whereas others could not substantiate this view (Volpitto et al 1944 Motley et al 1948) All these authors used inferential evidence mostly derived from determinations of blood pressures pulmonary ventilation or indirectly measured cardiac output Even the venous drainage records of Rost (1932) permit various interpretations which do not decide the issue

Thus there has been a lack of unequivocal evidence to resolve the crucial question Does intermittent positive *negative* pressure respiration result in a *net* increase of venous return over that existing during intermittent positive pressure breathing ?

We decided therefore to measure venous return directly in order to find out whether or not intermittent positive negative pressure respiration aids the circulation

The experimental arrangement was essentially the same as that used for the measurement of venous return during natural breathing In order to rule out any possible side effects from the opening and closing of the chest a number of experiments were performed in which the chest was not previously opened In these flow was measured with the catheter flowmeter illustrated in Fig 12 The results were the same as those in other experiments in which a thoracotomy had been made A Pitotmeter (Fig 11B) or a bristle flowmeter (Fig 15) was inserted following the thoracotomy the chest was then closed (Brecher 1953 Hubay et al 1954) The trachea was connected either directly or via intubation to a positive negative pressure respirator

FLOW IN NORMOVOLEMIA

The effect of intermittent positive and intermittent positive negative pressure breathing on venous return in the superior vena cava of a dog with normal

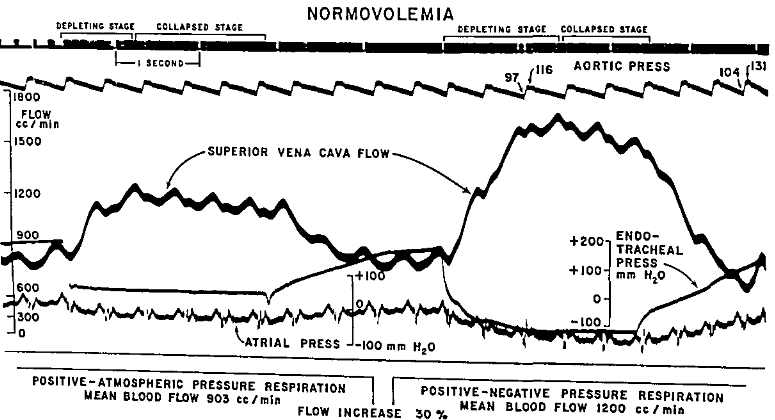


FIGURE 42 Augmentation of venous return by the application of positive negative pressure respiration in the closed chest of a normovolemic animal. Venous return is measured with a 5/31 bristle flowmeter (see Figure 15) in the superior vena cava. The cardiac variations of flow are smoothed out partially by means of an integrator in the amplifier of the flowmeter. Tracings from top to bottom: time, aortic pressure in mm Hg, superior vena caval flow in cc/min, endotracheal and right atrial pressures in mm water.

blood volume is illustrated in Fig 42 This shows a segment of a long record at the place where one type of respiration (alternating positive atmospheric pressure) is changed over to another (alternating positive negative pressure) From left to right the tracings reveal that positive pressure lung inflation greatly reduced flow but that flow increased rapidly upon sudden release of the lung inflation to atmospheric pressure This resulted from the backlog of blood that rushed from the peripheral veins to the heart The flow increased (depleting stage of the extrathoracic veins) and then leveled off (collapsed stage) Right atrial pressure was below zero indicating the existence of normal thoracic aspiration when the airway pressure was atmospheric During the next positive pressure phase flow was again reduced Next followed the negative pressure phase during which flow was greatly augmented It is obvious that this augmentation of flow is the result of the backed up blood *plus* the depleting of the extrathoracic venous reservoir by the greater thoracic aspiration The next positive phase reduced flow again as shown on the right side of the record This flow reduction was slightly greater than that observed during the positive phases which alternated with atmospheric pressure The greater flow reduction however did not cancel the flow increase which occurred during the preceding negative phase

On the right side of Fig 42 it is noted that the aortic pressure rose from 116/97 to 131 104 This significant rise in the arterial pressure is evidently the result of the increased venous return The rise was delayed by about 3 to 4 heartbeats after the onset of the venous flow augmentation because the blood had to circulate through the pulmonary bed These findings emphasize the immediate causal relationship of changes in venous return and aortic pressure

Mean flow in the superior cava calculated for two complete positive atmospheric pressure cycles was 903 cc min The corresponding measurement during the two positive negative cycles was 1200 cc min This is a *net* flow increase of 33 per cent

In the experiment illustrated in Fig 42 only mild positive pressure lung inflation was employed Flow was measured in numerous experiments over long periods of intermittent positive and positive negative pressure breathing With the latter type of respiration flow was always augmented It was generally found that the net flow increase became relatively greater during positive negative breathing if the lungs were inflated with higher pressures during the positive phases Similar flow augmentations as demonstrated in the superior vena cava in Fig 42 were also seen when measured either in the inferior cava separately or in both caval veins simultaneously

Summarizing

The application of intermittent positive negative pressure respiration augments venous return significantly over that existing during intermittent positive atmospheric pressure respiration The net increase of venous return caused by the negative phase is brought about by thoracic aspiration acting similarly to the mechanism operative in spontaneous respiration

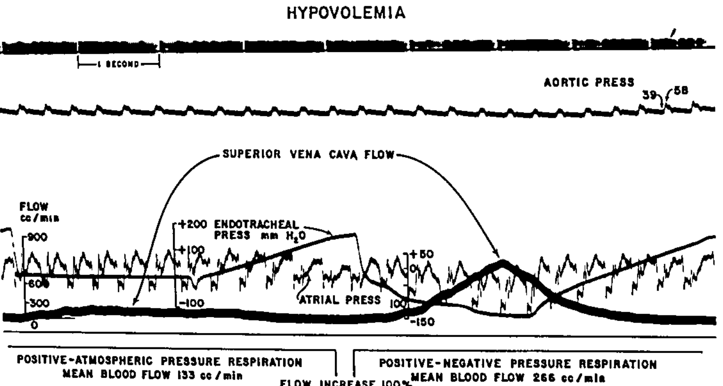


FIGURE 43. Augmentation of venous return by the application of positive negative pressure respiration in the closed chest of a hypovolemic animal illustrating the relatively greater net increase of flow in hypovolemia as compared to normovolemia shown in Figure 42. (Tracings as in Figure 42.)

Flow in Hypovolemia

It has been often observed that an increase of positive pressure in the airway of patients in shock or in poor circulatory condition is dangerous (Beecher et al 1943) Experimental support for this observation was furnished by Carr and Essex (1946) and Maloney and Handford (1954) who demonstrated that positive pressure respiration is especially detrimental when hypovolemia is present It was therefore of interest to see whether the use of a negative phase between positive pressure lung inflations would tend to alleviate these adverse effects

This was studied by creating a hypovolemic status in closed chest dogs by bleeding them until their mean arterial blood pressure was reduced to about 50 mm Hg Figure 43 depicts a segment of a record illustrating the deleterious effect of positive atmospheric pressure breathing and the beneficial effect of positive negative pressure respiration on venous return during hypovolemia For easier comparison the record is taken from the same experiment which is illustrated in Fig 42 It is seen (left) that venous return was very small during positive atmospheric pressure respiration but was greatly augmented (right) by negative pressure Although mean blood flow during positive atmospheric respiration was only 133 cc /min mean flow during positive negative breathing increased to 266 cc /min when each was measured Over two complete respiratory cycles this is a 100 per cent *net* increase of flow

It should be recalled that in normovolemia the addition of negative pressure in the closed chest of the same animal resulted in a net flow increase of 33 per cent The *absolute* flow increase by the use of the negative pressure phase in hypovolemia (133 cc) was *not* so great as in normovolemia (297 cc) since the content of the peripheral reservoirs was greatly reduced However the flow augmentation was relatively greater in hypovolemia since the initial volume flow rate was very low

Three facts derived from the flow curves in Fig 43 should be emphasized (1) Positive lung inflation resulted in almost complete cessation of flow (2) Atmospheric pressure did not create a favorable enough pressure gradient between the peripheral veins and the right atrium to deplete adequately the backed up blood into the thoracic veins (3) Decrease of the pressure gradient from the peripheral veins to the heart emptied the small peripheral venous reservoirs more effectively

As already demonstrated in the case of normovolemia arterial pressure also rose in hypovolemia as a result of the increase in venous return (from 43/35 to 58/39)

Summarizing

Use of intermittent positive negative pressure respiration in hypovolemia augments venous return relatively more than does the same type of respiration in normovolemia

Venous Return in the Open Chest

From the experiments presented in Figs 42 and 43 it is apparent that increased thoracic aspiration is the mechanism responsible for the augmentation

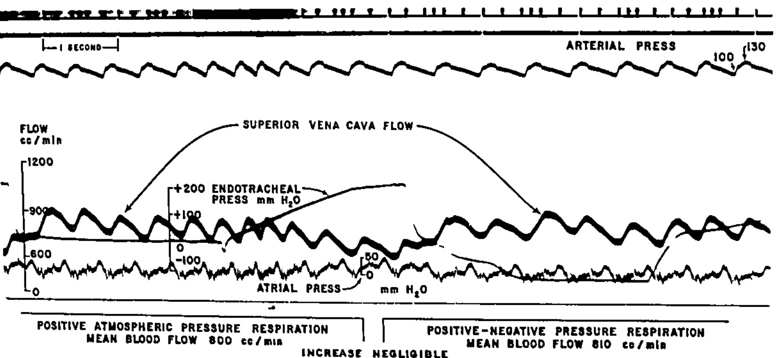


Figure 41. Insignificant increase of venous return upon application of negative endotracheal pressure between positive pressure lung inflations in the open chest. (Tracings as in Figure 42.)

of venous return during positive negative breathing If this is true it should be expected that after thoracic suction is abolished by opening the chest venous return could not be improved by the use of positive negative pressure respiration

This is demonstrated by a record in Fig 44 The segment corresponds again to those shown in Figs 42 and 43 The very end of a positive pressure lung inflation and the sudden release of endotracheal pressure to atmospheric value is seen at the extreme left of the record Superior vena caval flow which was reduced during the lung inflation increased immediately upon release of the positive pressure in the airway The next lung inflation seen in the middle of the record showed the same reduction of flow This inflation was followed by the application of negative pressure to the airway (right side of record) It did not result in a substantial increase of flow over that observed during atmospheric endotracheal pressure During two complete positive atmospheric respiratory cycles superior caval flow amounted to 800 cc min whereas during two positive negative cycles it was 810 cc min Other experiments in which venous return was measured simultaneously with cardiac output also showed that cardiac output did not improve by intermittent positive negative pressure respiration in the open chest (Hubay and Brecher 1956)

Summarizing

In the open chest the *net* flow increase by the application of positive negative pressure respiration is negligible

Venous Return and Cardiac Output During Artificial Respiration

Baxter and Pearce (1951) observed a significant pulmonary arterial flow augmentation during the negative phase of intermittent positive negative pressure respiration in the closed chest of the cat They felt that this might be due to an increase of venous return Therefore studies were made to see if such a causal relationship actually exist (Brecher and Hubay 1956)

The effects of intermittent positive atmospheric and intermittent positive negative pressure respiration on venous return and cardiac output in a closed chest normovolemic dog are illustrated in Fig 45 As in the records shown in Figs 42 and 44 a segment was chosen in which one type of respiration was changed to another As representative of venous return superior caval flow was recorded with a bristle flowmeter of the type depicted in Fig 15 Simultaneously total right heart output was recorded by measuring flow directly in the trunk of the pulmonary artery with the modified bristle flowmeter illustrated in Figs 16 and 17 Venous flow (second curve from bottom) followed the same pattern described before It was reduced during positive pressure lung inflation and increased particularly when suction was applied to the trachea Cardiac output (third curve from bottom) was also reduced during the lung inflations but not to the same extent as venous return It was also increased during the negative phase

It is noted that the change in cardiac output always took place *one heart beat after* the changes in venous return This lag was particularly striking when venous return increased upon the application of negative endotracheal pres

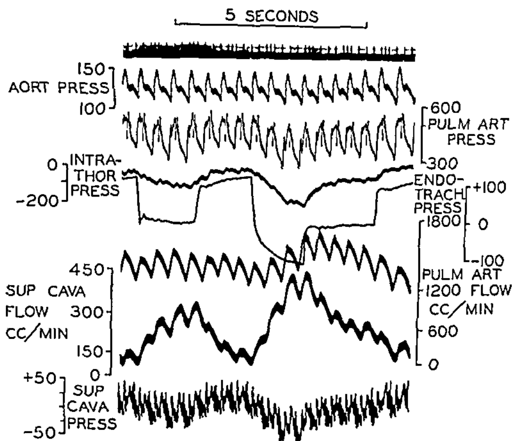


FIGURE 45 Relation of venous return to cardiac output during intermittent positive atmospheric and positive negative pressure respiration in the closed chest Tracings from top to bottom time and base line aortic pressure in mm Hg intrathoracic and endotracheal pressures in mm water pulmonary arterial and superior vena caval flows in cc/min superior vena caval pressure in mm water Description in text (Unpublished record of Hubay and Brecher)

sure and decreased when pressure in the trachea returned to atmospheric level Endotracheal pressure (fourth tracing from bottom) was transmitted into the thoracic cavity as indicated by the changes in intrathoracic pressure (fifth tracing from bottom) The pressures in the superior cava pulmonary artery and aorta followed the expected trends After a delay of several heart beats aortic pressures rose from 145/116 to 155/122 as a result of the augmented venous return and right heart output (Fig 45 right side uppermost curve)

From the time sequence of the hemodynamic events displayed in the pressure and flow tracings one can conclude that the increase of right heart output is the direct result of the augmentation of venous return which itself is caused by increased thoracic suction

The measurement of mean flow during 3 complete respiratory cycles revealed that superior caval flow was increased from 540 to 630 cc/min and cardiac output from 1430 to 1630 cc/min by the use of thoracic suction between lung inflation

Summarizing

Intermittent positive negative pressure respiration augments right heart output significantly over that prevailing during intermittent positive pressure breathing The changes in cardiac output are directly caused by the alterations in venous return during these two types of respiration

FLOW DURING LUNG INFLATION IN THE OPEN CHEST

It has been often observed that in the open chest venous return decreases during positive pressure lung inflation (see Fig 44) (Brecher and Mixter 1953 Mixter 1953, Brecher 1954 Hubay et al 1954) The genesis of this decrease in flow is not clear It could be caused by a primary hindrance to inflow into the right heart such as Humphreys and his associates (1939) have suggested or be secondary to an increase in resistance to flow in the pulmonary bed as suggested by Ankeney et al (1954) Experiments were therefore designed to determine how much of the flow reduction is actually caused by an impairment of right heart filling and how much by an increase in pulmonary resistance (Hubay et al 1955)

Figure 46 shows a diagram of the experimental arrangement Flow was measured with two bristle flowmeters in the right and left branch of the pulmonary artery Changes in pulmonary resistance through lung inflation could be eliminated by temporarily shunting blood from the right pulmonary artery into the left atrium while clamping the left pulmonary artery simultaneously The aim was to discover if outflow from the right heart (approximating venous return) would change during lung inflation even if resistance to output remained constant as it does in the tubing of the shunt

The record shown in Fig 47 illustrates the effect of positive pressure lung inflation when the total pulmonary blood flow passed through the right lung The flow tracing appears as a heavy black undulating line (electrical signal integrated in amplifier) Segment A is the control flow with atmospheric pressure in the airway Blood flow was 1 403 cc /min With lung inflation flow was reduced to 1 237 cc /min as shown in segment B a flow reduction of 11 9 per cent Figure 48 shows two corresponding segments of the same record taken ten seconds later after flow was diverted by merely opening the shunt to the left atrium and clamping the tubing leading to the right pulmonary vascular bed Section A is again a control flow measurement during atmospheric pressure in the airway Flow amounted to 1 652 cc /min it was reduced during lung inflation in segment B to 1 610 cc /min

The 2 7 per cent reduction shown in this record is so close to the limit of precision of the method as to carry little weight However in all of the records of this type of experiment a reduction was observed consistently during *each* lung inflation On this basis the recorded reduction is considered to be real

One may deduce from these findings that the 11 9 per cent flow reduction during lung inflation in Fig 47B was *mainly* caused by an increase of resistance in the pulmonary vascular bed because flow was less reduced (2 7 per cent) when the resistance remained constant (shunt flow section B Fig 48B) Hence the major factor reducing venous return during lung inflation in the open chest is the increase of resistance in the vascular bed Other factors which obviously

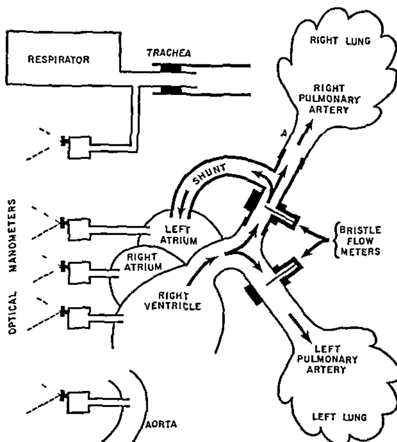


FIGURE 46 Diagram of experimental arrangement for shunting pulmonary blood flow (open chest dog). For technical simplicity the shunt leads from the right pulmonary artery to the left atrium. Throughout the experiment flow through both lungs is simultaneously recorded with two flowmeters. For testing the effect of pulmonary bed resistance on venous return total right heart output is diverted to the right pulmonary artery by temporarily occluding the left pulmonary artery. The right lung can then either be perfused by clamping the shunt or bypassed by clamping the right pulmonary artery at A.

must reside outside the pulmonary circuit play a minor role. Nevertheless their existence should not be neglected. They can be characterized as a mechanical compression or "tamponade" of the heart and great vessels by the expanding lungs which occurs even in the open chest.

Summarizing

Two etiological factors account for the reduction of venous return during positive pressure lung inflation in the *open* chest. Quantitatively the most important factor is an increase in pulmonary bed resistance which secondarily diminishes venous return. A less important factor is the "tamponade" of the heart and great vessels which primarily reduces right heart filling.

Clinical Implications

At first glance these basic experimental findings may not seem to be of great clinical importance. Wide clinical experience has shown that in the closed chest

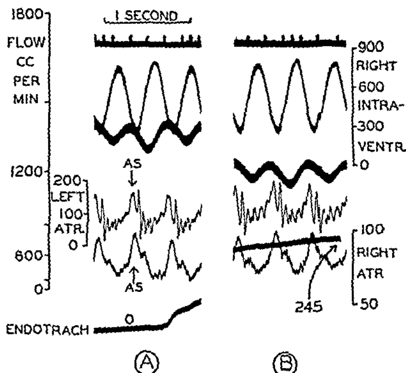


FIGURE 4. *Effect of positive pressure lung inflation on total pulmonary blood flow through the right lung when the left pulmonary artery is occluded (open chest).* Segment A flow and pressure tracings during atmospheric airway pressure (endotracheal 0). Segment B same tracings during lung inflation with endotracheal pressure of 245 mm water. Tracings from top to bottom: time, right intraventricular pressure in mm water, mean total pulmonary blood flow in cc/min, left and right atrial pressures in mm water, endotracheal pressure in mm water. AS = atrial systole. Time interval between end of segment A and beginning of segment B is 0.9 sec.

the use of intermittent positive pressure respiration is safe in normovolemic patients and individuals in good circulatory condition. The detrimental effect of positive pressure in the airway is easily overcome by a rise in peripheral venous pressure, increased autonomic activity and mobilization of blood reservoirs leading to a more favorable pressure gradient between the peripheral veins and the right atrium with an adequate blood flow into the central veins. A slight reduction of cardiac output is unimportant during many operative procedures or even desirable during some of them.

However, under conditions of blood loss, hypotension or shock, reservoirs are not available to allow this compensatory rise in pressure gradient favoring inflow and the poor venous return is diminished further by intermittent positive pressure respiration. The animal experiments furnish direct evidence that in such cases the use of intermittent positive negative pressure breathing can improve venous return and cardiac output. The considerable net increase of venous return makes a greater turnover of the available blood possible.

With the chest open, venous return is always impeded by positive pressure lung inflation. The animal experiments have clearly demonstrated that in the

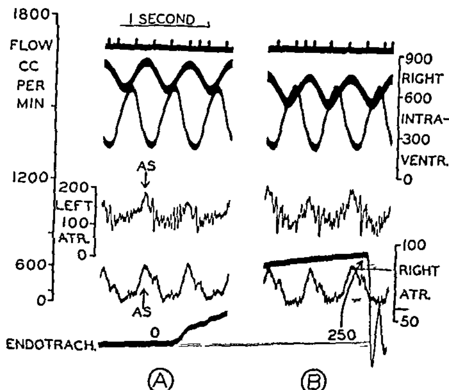


FIGURE 48 Effect of positive pressure lung inflation on total pulmonary artery flow which by-passes the lungs (open chest) The left pulmonary artery is occluded and the total blood is shunted through a tube from the right pulmonary artery to the left atrium Segment A flow and pressure tracings with atmospheric pressure in airway (endotracheal 0) Segment B same tracings with endotracheal pressure of 250 mm water Sequence of tracings as in Figure 47 AS = atrial systole Time interval between end of segment A and beginning of segment B is 0.8 sec

open chest the interposition of a suction phase between lung inflations does *not* benefit venous return or cardiac output because the mechanism of thoracic aspiration is absent Therefore, from this hemodynamic point of view positive negative respiration offers no advantage over positive atmospheric respiration in patients undergoing thoracic surgery This is not to deny that positive negative pressure ventilation during open thoracotomy may have a beneficial effect in other respects for example in reducing the CO tension in the arterial blood as demonstrated by Nealon et al (1955)

Since the decrease of right heart output during lung inflation in the open chest could be attributed to both an increase of pulmonary bed resistance and a tamponade of the heart and great vessels caution should be employed in inflating the lung The clinical practice of using *prolonged* positive pressure to aerate atelectatic lungs should be avoided as should also *excessive* inflation of the lungs which may interfere with the heart's filling Admittedly in patients with an adequate circulatory reserve compensation for such derangement is commonly observed but in patients who have lost blood or who are otherwise in a poor circulatory condition the effect may be very detrimental

Summarizing

In the closed chest the use of intermittent positive negative pressure respiration may benefit patients who are in poor circulatory condition because it facilitates their venous return However this type of respiration is not beneficial for increasing venous return in patients during open thoracotomy Excessive lung inflation in the open chest interferes with venous return by an increase of pulmonary bed resistance as well as by a tamponade of the heart and great vessels

IX Effect of the Heart's Action on Venous Return

In order to study the forces by which the heart itself may contribute to the return flow of blood it is necessary to obtain accurate information about the rapid variations of venous return within the cardiac cycle (see page 27). The 5734 bristle flowmeter was specifically developed for this purpose (see Fig. 15).

In these experiments meticulous care was taken to preserve the anatomical relations of the heart and its neighboring structures. The pericardium was not opened and whenever the chest was closed the normal intrathoracic pressure relations were re-established. These points are important for an evaluation of the forces which are normally responsible for cardiogenic flow changes.

Central Venous Flow Pattern

When a bristle flowmeter was inserted into the superior vena cava at the entrance of the right atrium numerous types of flow curves were obtained. A representative curve is shown in Fig. 49 illustrating flow changes during the cardiac cycle in the open chest. The time correlation is given by the simultaneously recorded right intraventricular and superior caval pressure curve. Right atrial inflow became greatly accelerated during ventricular contraction (Fig. 49, 2 to 4) and again slightly accelerated during ventricular diastole. The greatest flow reduction occurred during atrial systole. Similar flow patterns were recorded in the inferior vena cava.

The amount of blood entering the right atrium from the superior vena cava can be determined by measuring the area under the flow curve. It was found that venous return was greater during ventricular systole when the tricuspid valves were closed and no blood could enter the ventricle (2.35 cc volume inflow from 1 to 4 in Fig. 49) than during ventricular diastole when the tricuspid valves were open and atrium and ventricle formed a common cavity (2.1 cc from 4 to 9 in Fig. 49).

Summarizing

Typical vena caval flow curves show two main summits, one during ventricular systole and the other during diastole. Venous inflow into the right atrium is large during the time when the tricuspid valves are closed.

The Active Ventricular Systole

The fact that the rate of volume flow in the central veins is greatly accelerated during ventricular systole when the blood is blocked from entering the ventricle indicates the existence of a strong frontal force which causes the acceleration. The explanation is as follows. The responsible force is the contraction of the ventricle itself which draws blood toward the heart. The descent of the atrioventricular junction during ventricular systole enlarges the great venous reser-

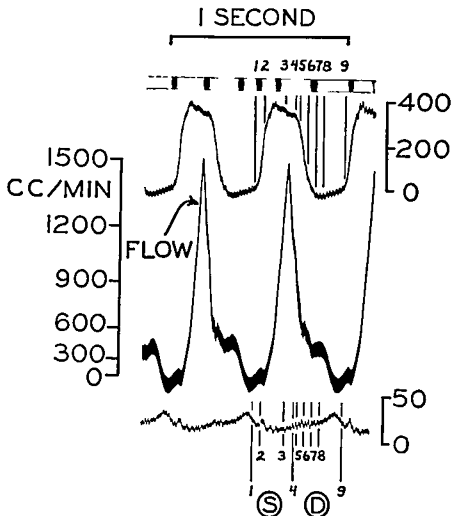


FIGURE 49 Venous return during different parts of the cardiac cycle (open chest) Tracings from top to bottom time right intraventricular pressure in mm water superior vena cava flow in cc/min superior cava pressure in mm water Numbers 1 to 9 denote the phases of the cardiac cycle S = systole D = diastole

voirs namely the atria and venae cavae Thus the piston like downward movement of the atrioventricular junction attracts blood from the central veins into the atrium (see Fig 1)

This view is supported by the following additional evidence from unpublished records of our laboratory (1) In a 2 1 or 3 1 block caval flow is stopped or briefly reversed during each atrial systole When the atrial systole is not followed by a ventricular contraction caval blood is *not* accelerated after the atrial muscle has relaxed (see also Nilsson and Kramer 1954) (2) In atrial fibrillation where the rapid atrial muscular contractions barely affect flow in central veins blood is *distinctly* accelerated during ventricular systole (3) The acceleration of venous flow during ventricular systole can be decreased by open

ing the pericardium or by removing the support of the heart in other ways In such cases the apex of the heart is often seen to move upward or sideways and the descent of the atrioventricular junction becomes less pronounced

The quantitative measurements of blood flow have thus furnished the heretofore missing *direct* evidence in support of the concept that the contraction of the myocardium itself draws blood toward the heart It establishes the existence of a substantial *vis a fronte* of cardiac origin

The function of ventricular contraction is, therefore, twofold It consists not only of the ejection of blood from the ventricle but also of the 'injection' of blood from the veins into the right atrium In other words the heart does not merely act as a pressure pump as William Harvey believed (1628) but it actually functions as a reciprocating pump (pressure suction pump) This is illustrated by a record shown in Fig 50 Superior caval flow was recorded simultaneously with total pulmonary artery flow It is noted that right atrial inflow was greatly augmented each time the right ventricle ejected its content The two tracings fit into each other like finger and glove making it easy to conceive the heart as a pressure suction pump

One may object to the use of the term 'suction' in this conection Suction implies the development of negative pressure A retracting piston connected to

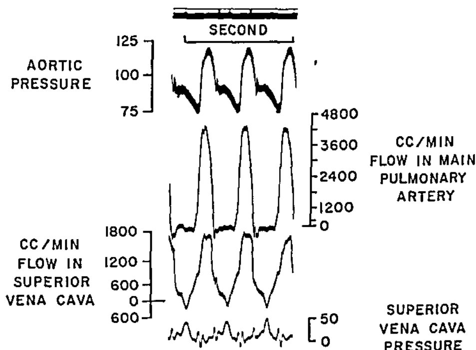


FIGURE 50 Action of the heart as a pressure-suction pump visualized by the simultaneous recording of inflow and outflow (open chest) Note the acceleration of venous return during ventricular ejection Right heart output recorded phasically with bristle flowmeter shown in figures 16 and 17 Superior vena caval flow recorded phasically with bristle flowmeter shown in figure 15 Tracings from top to bottom time aortic pressure in mm Hg pulmonary arterial and superior caval flows in cc /min superior caval pressure in mm water (Unpublished record of Hubay and Brecher)

a rigid walled tube system creates a negative transmural pressure The same piston (A V junction) connected to a *collapsible* tube system (atrium) *cannot* create a negative transmural pressure because the collapsible walls (atrial walls) are compressed by the extramural pressure In either case the fluid is pulled toward the piston by the creation of a low pressure near the retracting piston In either case the force (ventricular contraction) which moves the piston creates *suction* regardless of the transmural pressure which becomes negative only in a rigid walled system but cannot descend below zero (atmospheric level) in a collapsible system This situation obtains in the atria and veins which are collapsible structures For this reason one cannot record negative transmural pressures in the atria during ventricular systole Atrial pressures can only descend to a very low value but not to less than zero in the open chest Subatmospheric atrial pressures occasionally recorded in open chest animals during ventricular systole are under suspicion of being due to recording artifacts At most they are only a few mm of water below zero and of very brief duration

Summarizing

Direct and quantitative evidence indicates that the ventricular myocardial contraction provides a *vis a fronte* which draws blood actively toward the heart during ventricular systole Hence the heart does not act as a pressure pump only, but as a pressure suction pump during ventricular contraction

Venous Return During Ventricular Diastole

It will be recalled that there is a relatively small acceleration of venous flow at the beginning of ventricular diastole (see Fig 49) It has generally been observed that with lower heart rates venous return becomes increasingly more prominent during ventricular diastole (Holzlohner and Schoenerstedt 1941, Brecher and Praglin 1953 Brecher 1954 Nilson and Kramer, 1954) The effect of different heart rates on the systolic and diastolic inflow into the atrium was therefore studied under strictly controlled experimental conditions (Brecher 1954)

In open chest dogs with a naturally slow heart rate the right atrium was stimulated with electrical shocks in order to produce faster heart rates without altering any other factors in the experiment Figure 51 illustrates the effect of different heart rates on venous return Segment A depicts two consecutive heart beats the first one with a long diastole and the second one with a short diastole Segment B reveals the flow pattern when the atrium was stimulated 3 times per second It is noted that the duration of systole changed relatively little with the acceleration of the heart and that venous return during each individual systole remained approximately the same On the other hand the diastolic return flow was large with bradycardia and very small with tachycardia Total superior caval volume flow per second remained about the same at all heart rates At a slow (83) heart rate 43 per cent of the blood entered the atrium during systole and 57 per cent during diastole At tachycardia (177) the corresponding flows were 81 per cent during systole and 19 per cent during diastole

This experiment demonstrates that the heart possesses a self regulatory

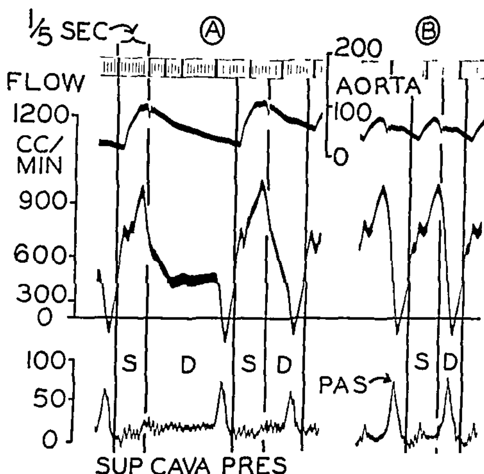


FIGURE 51 Effect of heart rate on inflow into the right atrium Venous return is physically recorded with a bristle flowmeter in the superior vena cava (open chest) Description in text Tracings from top to bottom time aortic pressure in mm Hg superior vena cava flow in cc/min superior vena cava pressure in mm water Note the brief reversal of flow during the peak of atrial systole (indicated as P.A.S in the superior vena caval pressure curve)

mechanism which keeps venous return constant within limits It does so by substituting during tachycardia the rapidly repeated active systolic attraction of blood for the diastolic inflow into the atrium which predominates at normal and slow heart rates This mechanism must be looked upon as an innate safety device of the heart by which it assures its own atrial filling with sudden cardiac acceleration such as may occur during stress or anxiety Knowledge of this mechanism makes it understandable why cardiac output can be maintained fairly well at *fast* heart rates

Under comparable conditions atrial inflow is usually larger in the closed than in the open chest during ventricular diastole This is illustrated in Fig 52 Flow was measured in the superior caval vein after chest closure Inflow during systole (S) was *less* than during diastole (D) In the middle of the record the endotracheal pressure was lowered and flow during the next two heart cycles increased due to thoracic aspiration The fact that in the closed chest atrial

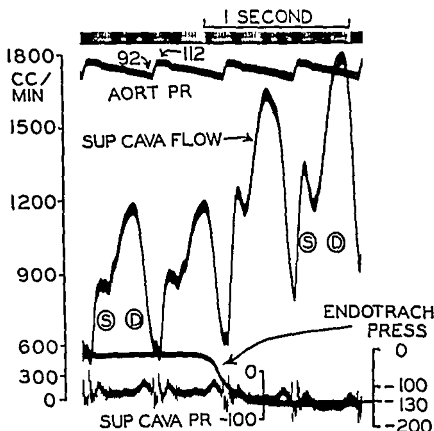


FIGURE 52 Effect of increased thoracic aspiration on venous return during ventricular diastole (closed chest) Endotracheal pressure in a closed system is lowered from atmospheric (zero) to −130 mm water Tracings from top to bottom time aortic pressure in mm Hg superior vena caval flow in cc/min endotracheal and superior vena caval pressures in mm water S = systole D = diastole

inflow is often larger during diastole than during systole suggests that negative intrathoracic pressure enters as an additional factor promoting venous return It acts apparently by a direct suction on the outside of the ventricular and atrial walls thereby expanding the heart's cavities passively and in turn permitting greater inflow from the venae cavae Furthermore the systolic attraction of venous blood by the descent of the atrio ventricular junction may be less pronounced in the closed than in the open chest This is supported by the observation of Rushmer (1955b) that the atrioventricular junction does not move so extensively in the closed as in the open chest

The question of whether or not the ventricle sucks blood from the atrium during diastole has not been resolved by these experiments It is generally concluded from the observations of von den Velden (1906) Straub (1912) Wiggers (1928) Cotton (1934) and Lazst and Muller (1930) that the absence of negative pressure in the ventricular cavity is sufficient evidence for the nonexistence of ventricular diastolic suction

However, a brief theoretical consideration reveals that the lack of negative intraventricular pressure, detectable with present techniques, does not necessarily prove the absence of a diastolic sucking force. It has been pointed out on page 107 that *negative pressure cannot develop in the atria because their walls are pliable* (= collapsible). It can be stated likewise that a detectable negative transmural pressure cannot develop in the ventricular cavity since the more rigidly walled ventricle forms a common cavity with the collapsible structures of the atrium and veins during diastole and resistance to flow from the atrium to the ventricle is negligible. *Even if the ventricle does suck in blood during diastole* it may not produce a detectable negative transmural pressure in the ventricle because the pliable walls adjoining atrium permit a form change of the atrium when it empties its content into the ventricle.*

Summarizing

The heart keeps its venous return relatively constant by shifting the *proportion* of its atrial inflow from the predominant inflow during the long ventricular diastasis of bradycardia to a large active inflow with tachycardia due to the rapidly repeated systolic attraction of venous blood. Owing to thoracic suction on the cardiac walls diastolic inflow is often larger than systolic inflow in the closed chest. The commonly accepted evidence for the nonexistence of ventricular *diastolic* suction (i.e. absence of negative intraventricular transmural pressure) is not necessarily conclusive. Negative transmural diastolic pressures and diastolic suction can occur in the intact mammalian ventricle when the residual volume is small.*

Phasic Inflow and Stroke Volume During Natural Breathing

Since cardiac output depends on venous return one is faced with the question of how cardiac output is related to the cardiogenic and respirogenic flow changes in the central veins under normal physiological conditions. This is of particular interest since it has been disputed whether in the closed chest, cardiac output could increase with spontaneous inspiration in view of the fact that the pulmonary arterial bed resistance is known to rise with inspiration (Edwards 1951, Baxter and Pearce 1951).

In order to elucidate the manner in which the dynamic changes in venous return and cardiac output are correlated during natural breathing phasic flow in the superior vena cava and the main pulmonary artery were simultaneously recorded with two bristle flowmeters (Brecher and Hubay 1955).

*While the manuscript was processed negative intraventricular transmural pressures ranging in average from 5 to −96 mm water were demonstrated in open chest dogs (Brecher 1956). Such negative pressures and diastolic suction could be demonstrated only when the collapsible structures (left atrium and pulmonary veins) were closed off from the ventricle. This was done for several heart beats by occluding the mitral orifice. The negative intraventricular pressure and suction is apparently caused by an elastic recoil of the ventricular walls. These experiments prove the existence of negative transmural ventricular pressures and of diastolic intraventricular suction in *the intact mammalian heart when the residual* volume is small. However no conclusion can be drawn as to the quantitative significance of diastolic suction for filling of a ventricle which contains a normal or large residual volume.

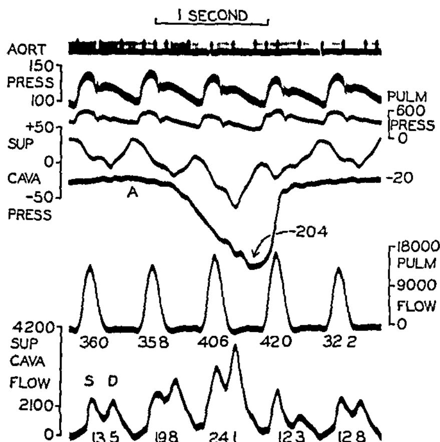


FIGURE 53 Effect of spontaneous respiration of venous return and cardiac output (closed chest) Tracings from top to bottom time and base line aortic pressure in mm Hg pulmonary artery superior vena caval and intrathoracic pressures in mm water pulmonary arterial and superior vena caval flows in cc/min A = beginning of inspiration S = acceleration of superior vena caval flow during ventricular systole D = acceleration of superior vena caval flow during ventricular diastole Stroke volume (in cc) under pulmonary arterial flow curve Flow (in cc) through superior vena cava during each cardiac cycle at bottom of record Electrical frequency response of both flowmeters reduced from 400 to 40 cycles/sec Superior vena caval pressure curve damped

Figure 53 is a segment of a record which illustrates the flow changes during five heart beats modified by the action of one respiratory cycle Flow in the superior vena cava (lowest tracing) is seen to increase during each ventricular systole (S) and again during each ventricular diastole (D) The amount of blood passing through the superior cava during each heart cycle (cc/cycle) was calculated from measurements of the area under the flow curve and entered in the record of Fig 53 under the tracing With the onset of inspiration (A) venous flow increased as early as the beginning of the second heart beat It reached its maximum during the third beat when inspiration became deeper During expiration venous flow became minimal and increased again during the respiratory pause

The changes in the stroke volume of the five heart beats are visible in the next to last tracing of Fig 53 Right heart output did not increase during the second heart beat despite the fact that venous return during the same heart cycle was already greatly augmented The output became largest during the fourth beat though venous return had become minimal and expiration had already started The smallest volume was ejected by the last beat when venous return was again on the increase

This record demonstrates that pulmonary artery flow increased significantly during spontaneous inspiration in spite of a small (but not significant) increase in pulmonary artery bed resistance Furthermore the increase or decrease in right heart output always came one heart cycle after the increase or decrease in venous return since the blood had to pass through the heart This sequence of events indicates that the augmentation of pulmonary artery flow with natural breathing was directly caused by the increased venous return and was not due to a reflex or an intrinsic mechanism of the right ventricle

The calculation of the stroke volume and caval flows per heart cycle shows that during inspiration right atrial inflow was relatively larger than outflow from the right ventricle * Thus, the increase in venous return must result in a dilation of the right heart during inspiration From this we must conclude that the right heart acts as a moderator for the pulmonary flow by temporarily storing part of the large influx of venous blood during inspiration and ejecting the stored part during expiration and the expiratory pause

Summarizing

Right heart stroke volume increases during spontaneous inspiration because venous return is augmented by the inspiration The right heart accommodates part of the large respirogenic influx of venous blood temporarily and releases it into the pulmonary circulation during the respiratory pause

Newer Concepts of the Heart's Action on Venous Return

The presently available evidence makes it necessary to adjust some of our thinking about the role of the heart in the return flow of blood The fact that ventricular contraction actively draws blood into the right atrium makes the heart itself a factor of primary importance in the regulation of venous return During ventricular systole the atrium not only fills passively with blood pushed by the left ventricle (*vis a tergo*) but due to the descent of the atrioventricular junction it also *ladles* blood from the cistern of the central veins *in accordance with its availability* for the subsequent ejection (see Fig 51) Thus a more sovereign role must be assigned to the heart than generally believed

The filling of the atrium during ventricular systole depends not only on the quantity and pressure of blood in the venous reservoir which may be available for passive inflow but also on the vigor with which ventricular systole moves the atrioventricular junction Thus a vigorous contraction (commonly associated with a large stroke output) ensures additional inflow into the atrium

* The same quantitative relation between superior caval flow and right heart ejection was also established for the inferior vena cava in other experiments (Hubay and Brecher unpublished data)

of any available blood and therefore facilitates the next large ventricular ejection without causing an extreme diminution in ventricular residual content

The immediate need of an increase in cardiac output is therefore automatically assured by the simultaneous increase of atrial inflow both mediated by the same force the ventricular contraction

The central veins are most suitable for this reservoir function because their content can change rapidly through a partial collapse of their walls accompanied by a very small change of pressure They form a *collapse chamber* which is the functional counterpart of the aortic *compression chamber* (Brecher et al 1953) On the arterial side it is the compression chamber (windkessel) based on the elastic distensibility of the walls which assure the transformation of the discontinuous cardiac ejections into steady flow for the tissues On the venous side it is the *collapse chamber* based on the pliability of the walls which assures the *transformation of the steady flow from the tissues into the pulsatile flow* at the atrial entrance which is needed for the discontinuous cardiac filling (compare extent of cardiogenic and respirogenic flow changes in abdominal and thoracic inferior vena cava in Fig 33)

The filling of the collapse chamber is aided by the atrial systole From a hemodynamic standpoint the function of atrial contraction is twofold (1) It adds a little blood to ventricular filling (this is a well established fact) (2) It enlarges the central venous reservoir by briefly stopping atrial inflow Hence an adequate amount of blood is readily available for the rapid emptying of the cistern by the next ventricular contraction The small amount of backflow which is often recorded during atrial systole at the caval atrial junction does not extend far into the periphery (Brecher 1954) It is readily taken up by a widening of the collapse chamber and together with the continued inflow from the periphery creates the pool from which the next ventricular filling derives its supply

It may be assumed that the situation observed for right atrial inflow prevails also for inflow into the left atrium (see also page 23) This is essentially true because the flow patterns in the pulmonary veins are similar to those of the caval veins However in recent (unpublished) experiments in which flow was recorded with one bristle flowmeter in a pulmonary vein and with another in a caval vein we found that atrial inflow during ventricular diastole was relatively larger into the left than into the right atrium One could speculate that either the greater *vis a tergo* through the low resistance pulmonary vascular bed or a greater facilitation of ventricular diastolic inflow (greater suction of the thick walled left ventricle?) may account for this difference

Although for reasons of clarity the respiratory and cardiac factors are considered here separately they act in an integrated manner in the normal organism This is best illustrated in Fig 53 which gives an idea of how both forces act simultaneously one supporting the other in drawing blood toward the heart The question arises now as to the relative contribution of these frontal factors and the *vis a tergo* in venous return It is doubtful if this question can ever be answered precisely

In a circularly arranged distensible and collapsible fluid filled system in which the fluid is kept in motion by two forces one pushing and one pulling

it is difficult to assess which force is the greater one at a given point in the circle The *vis a fronte* created by both the inspiratory and ventricular muscle contraction lowers atrial pressure and thereby increases the pressure gradient between the capillaries and the heart Even a small decrease of atrial pressure can be expected to have a great effect on flow because of the low resistance in the venoatrial inflow tract as compared to the high resistance encountered in the arteriolar and capillary bed How much this lowering of atrial pressure could promote flow in the absence of a *vis a tergo* would not be easy to assess under physiological conditions However it appears that the pressure gradient between the capillaries and the right heart is created by the concerted action of *both* forces the *vis a tergo* which is mainly responsible for the *height of capillary pressure* and the *vis a fronte* which is mainly responsible for *lowering the level of the right atrial pressure* Both forces work together for the return flow of blood

Summarizing

The heart assumes a relatively sovereign position concerning venous return by actively ladling blood from the venous cistern in accordance with its availability for the next ejection The ventricular contraction automatically assures a coordination of the amount of inflow and ejection The pliable central veins form a collapse chamber which assures the transformation of steady flow from the tissues into discontinuous flow for the filling of the heart The collapse chamber is the venous counterpart of the compression chamber Atrial contraction stops atrial inflow and creates a large central venous reservoir available for rapid atrial filling through the next ventricular contraction The *vis a fronte* created by the myocardial and inspiratory muscles is integrated in the normal organism The *vis a fronte* appears to be mainly responsible for lowering the level of atrial pressure whereas the *vis a tergo* is responsible for the height of the capillary pressure The combined action of both creates the pressure gradient necessary for the return flow of blood

X Venous Hemodynamics of Cardiac Valve Lesions

It is obvious that the normal cardiac variations in venous return are altered by changes in the dynamics of the heart In this respect the changes produced by lesions of the atrioventricular valves and by pericardial tamponade are of particular interest since their surgical correction has become very promising in recent years Unfortunately our information on venous return in the presence of valvular defects and of pericardial tamponade is not yet based on quantitative measurements of phasic flow but is predominantly derived from indirect evidence of pressure determinations This discussion must therefore be limited to a brief review of several factors concerned with the changes of venous flow dynamics in the presence of these lesions It is not intended as a review of the hemodynamics of all valvular defects a subject which is extensively covered in other accounts by Harrison (1954) Luisada (1954) and Wiggers (1952 1954)

Mitral and Tricuspid Insufficiencies

It is well known that the circulation can be adequately maintained in pure mitral or tricuspid insufficiencies of moderate degree (Gorlin et al 1952 Barger et al 1952) Regurgitation does not appear to be so great as one might expect from the extent of the anatomical lesion The intriguing hemodynamic question arises Why is not the *entire* ventricular volume of blood regurgitated through the open ventricular orifice into the low pressure system of the atria and veins? The amount of blood that is regurgitated during ventricular systole appears to be limited by the combined action of several factors Four of these should be pointed out here

1 In experimentally produced mitral and tricuspid insufficiencies only a negligible amount of blood is regurgitated during the phase which corresponds to the isometric ventricular contraction of the normal heart During this phase a sufficiently high intraventricular pressure is created for opening the semilunar valves and subsequent ejection of part of the blood into the high pressure system of the arteries Back flow into the atria and veins is not appreciable until the beginning of the systolic ejection phase (Wiggers and Feil 1922 Little 1948)

It can be demonstrated in physical models that the amount of back flow during isometric contraction seems to depend upon the *rate* at which pressure develops in the ventricle (Wiggers and Feil 1922 Wiggers 1952 Liebau 1954 1955) If a *sudden* pressure rise is created by compressing a fluid filled rubber balloon the amount of fluid displacement from the balloon into adjoining open bottles is relatively small This sudden compression would correspond to the isometric ventricular contraction According to this analogue sudden ventricular contraction may develop enough pressure to open the aortic valves without an

appreciable fluid displacement from the ventricle into the atrium. On the other hand, a slow compression of a rubber balloon will result in a major displacement of fluid into an adjoining low pressure system (atrium), before sufficient pressure for opening a valve toward an adjoining high pressure system (artery) develops.

2 During ventricular ejection regurgitation may be impeded by a narrowing of the atrioventricular ring. It is believed that the contracting ventricular muscle bundles effect this so called muscular contraction of the atrioventricular ring. By inserting a finger through the atrial appendage one can easily palpate the narrowing of the ring during ventricular systole. Convincing visual evidence for the systolic narrowing of the mitral ring has been presented by Kantrowitz et al (1951) in a motion picture of the opened dog heart.

3 A partial occlusion of the atrioventricular orifice by the contracting ventricular myocardium is supposed to aid in limiting regurgitation.

4 The maintenance of some leaflet mobility limits the amount of back flow. Mobile leaflets permit by their valve action the inflow of a larger amount of blood during ventricular diastole than is regurgitated during systole.

The rationale of several procedures for the surgical correction of mitral insufficiencies is based on the remaining mobility of the incompetent leaflet (Harken et al 1954 Harken 1955 Bailey 1955 Bailey et al 1955). During diastole these leaflets form a large valve aperture which permits adequate ventricular filling. However during systole they do not close sufficiently and leave an "aperture of incompetence" through which a jet of blood is ejected back into the atrium. Functional competence of the atrioventricular valves can be reestablished by merely abolishing the aperture of incompetence. This may be accomplished by various baffles grafts or plicate which occlude the aperture (Bailey Jamison et al 1954 Bailey 1955 Bailey et al 1955 Harken et al 1954 Harken 1955) or by a judicious reduction in the size of the atrioventricular ring (Davilla et al 1955 Bailey et al 1955 Benchoux and Chalnot 1955). Immobile leaflets may be suitably mobilized prior to the correction of the insufficiency.

In mitral and tricuspid insufficiencies atrial pressure rises during ventricular systole due to the regurgitation of the ventricular blood plus the atrial inflow from the veins. The rise of atrial pressure creates a high atrioventricular pressure gradient for the next diastole (Wiggers and Feil 1922 Little 1948). This results in a more rapid and greater filling of the ventricle than normally. The ventricle accomodates during diastole the regurgitated blood plus the normal venous return. The resulting ventricular dilatation may widen the atrioventricular ring and in turn increase the already existing insufficiency of the leaflets. As this leads to greater regurgitation it establishes a vicious cycle which is considered characteristic for the self aggravating nature of the insufficiencies. Partial blocking of the leak alone may therefore result in a reduction of the atrioventricular annulus merely by decreasing the ventricular dilatation (Harken et al 1954 Harken 1955).

Phasic changes of venous return in tricuspid insufficiency have been directly recorded in the unanesthetized human by Muller and Shillingford (1955). Using a double lumen Cournand catheter with a differential manometer they demon

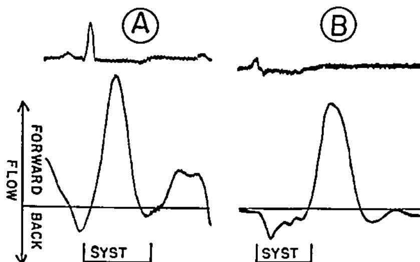


FIGURE 54 Blood flow between the superior vena cava and right atrium in a normal subject (A) and one with tricuspid incompetence and high venous pressure (B) (Redrawn from an original record of Muller and Shillingford 1955)

trated directional change of flow in the presence and in the absence of a tricuspid insufficiency Fig 54A illustrates superior caval flow in a normal subject During atrial systole flow was briefly reversed Forward flow reached its maximum in ventricular systole stopped briefly at the end of systole and was again accelerated during ventricular diastole The similarity of this flow pattern and those obtained in experimental animals suggests that fundamentally the same hemodynamic events determine venous return in the mammalian heart It should be pointed out though that the tracings in Fig 54 are not a quantitative measure of flow since the cross sectional area of the vessel was not fixed and an overshoot in both directions could be caused by large fluid columns in the catheters and by the distance between the holes of the catheter (10 cm apart one in the atrium and the other in the superior vena cava) In a subject with tricuspid insufficiency flow was reversed during ventricular systole and greatly accelerated during diastole (Fig 54B)

Summarizing

The normal rapid forward movement of central venous blood during ventricular systole is reversed in the presence of a large atrioventricular valve insufficiency Maximal forward flow occurs under these circumstances during ventricular diastole Vigorous ventricular contraction may produce enough pressure in the ventricle to open the aortic valves without causing an appreciable fluid movement from the ventricle into the atrium through the orifice Narrowing of the atrioventricular ring and partial occlusion of the leak during ventricular contraction may hinder regurgitation into the atrium In the surgical correction of some insufficiencies one can utilize the maintenance of leaflet mobility which limits the amount of back flow during ventricular systole

Mitral and Tricuspid Stenoses

The great technical difficulties encountered in creating experimentally a mitral or tricuspid stenosis similar to a natural one are in part responsible for the meager knowledge of phasic changes in venous return in the presence of these lesions (Katz and Siegel, 1931 Opdyke and Brecher, 1951, Hamilton et al, 1954) On the basis of physically recorded pressures acute mitral stenosis appears to affect venous return as follows Increased resistance to flow offered by the small mitral orifice is in part overcome by increased left atrial pressure, more vigorous atrial muscle contractions and a prolonged ventricular filling time Hence a steep left atrioventricular pressure gradient is characteristic for mitral stenosis Total systemic and pulmonary venous return are diminished (Katz and Siegel 1931) Pressure measurements in humans reveal particularly that a decrease in the duration of ventricular diastole reduces ventricular filling The diastolic filling period may be shortened by either an increase in heart rate or a relative prolongation of ventricular systole Thus, in mitral stenosis moderate tachycardia alone may lead to bouts of pulmonary edema by backing up of blood in the pulmonary veins (Gorlin et al 1951) Since mitral stenosis is often associated with some insufficiency (incompetence of the rigid leaflets) regurgitation into the left atrium occurs generally during ventricular systole The amount of regurgitation is again determined by the physical factors discussed above

The production of an acute interatrial septal defect for the relief of pulmonary venous congestion in mitral stenosis is without detectable dynamic effect (Opdyke and Brecher 1951) It appears therefore doubtful whether the creation of an interatrial septal defect would be beneficial for the relief of pulmonary congestion in cases of human mitral stenosis

The greatest improvement of venous return is achieved by the surgical correction of the stenosed atrioventricular valves (commissurotomy valvuloplasty valvotomy) In this operation the valves are adequately separated either by a finger or with the aid of a suitable instrument such as a commissurotomy guillotine or dilator (Cooley and DeBakey 1954 Glover, 1954 1955, O'Neill et al 1954 Bailey 1955) Much of the valve motion can be restored when the valves are separated at the full length of the commissure The commissurotomy reduces immediately the high atrial pressure It results in a significant decrease of the mean diastolic atrioventricular pressure gradient This fall appears to parallel the improvement in venous return (Gordon et al 1954 Yu et al 1954)

In some respects the hemodynamic events in tricuspid stenosis are similar to those described for mitral stenosis Ferrar et al (1953) found in catheterization studies of a patient with tricuspid stenosis that her atrioventricular pressure gradient remained steep during ventricular diastole Apparently the right ventricle is filling throughout this entire period The stenosed valves do not open sufficiently in diastole Hence they prevent the early inrush of blood into the ventricle which is so important for normal ventricular filling In pure tricuspid stenosis right atrial pressure increases very much during atrial systole and falls continuously during isometric ventricular contraction and early ventricular ejection The impediment to venous return by tricuspid stenosis leads

to the well known clinical syndrome of congestive failure which is beyond the scope of the present discussion

Summarizing

Elevation of atrial pressures increases the atrioventricular pressure gradient in mitral and tricuspid stenosis. The small orifice prevents rapid ventricular filling at early diastole, making the filling more dependent on the existence of a long diastole. Commissurotomy of the stenosed atrioventricular valves results in an immediate and lasting improvement of venous return.

Pericardial Effusion

A discussion of circulatory changes resulting from pericardial effusion is included in this chapter because in some hemodynamic respects these changes resemble those caused by valvular disorders. Pericardial tamponade has often been produced in acute and chronic form in animal experiments by infusing saline solution or other fluids into the pericardial sac (Nerlich 1951, Metcalfe et al 1952, Boucek et al 1952a). Present knowledge of the hemodynamic alterations is mainly derived from pressure measurements.

When in animal experiments involving the acute form, the pericardial sac is progressively filled with saline, venous return is at first impaired only during ventricular diastole since the pericardial tamponade hinders the expansion of the atrioventricular cavity. Hence the stroke volume becomes smaller. Ventricular ejection decreases the pericardial pressure and by reducing the impediment to atrial filling creates a more favorable veno atrial pressure gradient (Nerlich, 1951). Further progression of the tamponade diminishes venous return not only during diastole but also during ventricular systole since atrial inflow is impeded. When the veno atrial gradient becomes diminished during ventricular systole, a self perpetuating cycle appears to develop. Nerlich suggests that the decrease of the systolic discharge reduces the facilitating effect of ventricular systole, whereupon the veno atrial pressure gradient becomes less favorable. This in turn diminishes ventricular filling and so forth.

When this phase is reached, venous pressures rise and arterial pressures fall abruptly. Finally with further effusion all intravascular pressures approach the same value of about 20 mm Hg when the heart ceases to pump blood effectively from the venous to the arterial side (Metcalfe et al 1952). The acute tamponade affects blood inflow into the right heart about to the same extent as it does inflow into the left heart.

Chronic experimental constrictive pericarditis in dogs can develop in such a manner that it interferes with the return flow of blood more on one side of the heart than on the other. If the tamponade primarily blocks left heart filling, it results in the development of pulmonary edema and a marked increase in blood volume. In such case systemic venous pressure does not rise significantly and ascites fails to develop. On the other hand, if the right inflow tract is primarily affected, systemic venous pressure rises and hind leg edema develops but pulmonary edema and changes in blood volume do not occur (Boucek et al 1952a). These two different types of circulatory failure can also be produced without pericardial involvement by constricting separately the pulmonary ve

nous inflow tract and the vena cava inflow tract to the heart (Boucek et al 1952b) In chronic experimental pericarditis the tamponade is relieved by a pericardial resection which must include the area of the pericardium overlying the inflow tracts It appears therefore that the pericardial tamponade acts primarily by restricting venous return at the inflow tracts of the heart The characteristic low cardiac output is the result of the restriction in venous return

Pressure tracings from the right atrium and ventricle in patients with chronic constrictive pericarditis before and after pericardiectomy seem to indicate that in pericarditis the systolic ejection of the heart is relatively less impaired than the diastolic filling (Hansen et al 1951) Early diastolic ventricular pressure in patients with pericarditis varies little from normal On account of the steep atrioventricular pressure gradient the ventricle begins to fill rapidly in early diastole but is limited in its further filling by the pericardial constriction This causes a marked rise of end diastolic ventricular pressure which is typical for these patients Shortening of the diastole by heart rate acceleration is fairly well tolerated because ventricular filling is limited anyhow to early diastole under these conditions

Summarizing

Pericardial tamponade reduces primarily ventricular diastolic filling Since the ventricle cannot eject without filling the low output is the most characteristic effect of pericardial effusion Predominance in the constriction of the left atrial inflow tract causes circulatory failure associated with pulmonary edema, whereas that of right atrial inflow tract leads to failure associated with ascites

XI Venous Return During Cardiac Surgery

From the considerations in the previous chapters it may be concluded that the combined action of anesthesia and open thoracotomy diminishes the circulatory reserve This can be accounted for by (1) a decrease in the pulmonary blood depot (2) heart shrinkage (3) the absence of the respiratory pump and (4) an increase in pulmonary bed resistance plus a tamponade of the heart and great vessels by positive pressure lung inflation Hence additional interference with venous return by cardiac surgery may result in further reduction of the narrowed circulatory safety margin Thus a brief account of some factors influencing venous return in cardiac surgery may not be amiss

It is not intended to consider here the effect of all heart operations on venous blood flow but rather to call attention to the application of some of the hemodynamic principles presented in the previous chapters For comprehensive reviews of the rapidly developing field of cardiovascular surgery reference is made to the International Symposium on Cardiovascular Surgery held at the Henry Ford Hospital in 1955 (report edited by Lam 1955) and the recent textbook on Surgery of the Heart by Bailey (1955)

During intracardiac surgery a number of methods are currently employed which may be divided into two general groups closed heart and open heart surgery In closed heart procedures the operative field within the heart is not directly visible In these cases the heart and great vessels remain filled with blood and the operating finger or instruments are introduced through a suitable incision in the wall of the atrium ventricle or vessel In open heart surgery the heart or adjoining vessels are briefly blocked off from the circulation by an occlusion of the systemic veins This permits direct vision of the operative field when the heart or vessels are opened and drained of blood

In either group it is essential to perfuse adequately the coronary vessels and brain during the relatively short period when the surgical procedures are carried out within the heart Temporary blocking or interference with venous return as such does *not* seem to be of major detriment to the organism as long as by some means or other sufficient nourishment of the myocardium central nervous system and kidneys is assured In closed heart surgery this must be assured by minimal embarrassment of the returning blood which after its oxygenation in the patient s lungs is ejected in a normal manner by the contraction of the ventricular muscle On the other hand in open heart surgery the same goal must be reached by direct perfusion of the arterial system under high pressure with oxygenated blood In this case it does not matter in principle whether the perfusing blood is taken from an infusion bottle or taken from the patient s veins and then used for perfusion after it has been collected and oxygenated

Closed Heart Surgery

In closed heart surgery venous return is mainly interfered with when the exploring finger and/or operating instruments are pushed into pathologically narrowed parts of the inflow or outflow tract This may be illustrated by the situation prevailing in the mitral or tricuspid stenosis In an operation for a lesion of this type the finger is inserted either alone or together with a guillotine knife or dilator into the atrium through an incision in the atrial appendage or wall (Glover 1954 1955 Dubost 1955) The insertion into the atrium in itself does not appear to hinder cardiac inflow Only the introduction of the finger and instrument into the mitral or tricuspid orifice for the purpose of separating the valve leaflets blocks ventricular filling Dubost (1955) has developed a special mitral dilator which he also used for tricuspid and pulmonary stenoses Manipulations can be carried out very fast with this instrument He points out that due to the speed attained with the dilator the atrioventricular orifice *is only obturated for two or three heartbeats*

In most cases of closed heart surgery the actual operative procedures at the site of the lesions are of relatively short duration By a suitable release of the instrumental inflow impediment the surgeon can usually control venous return sufficiently to permit the development of adequate arterial pressure and flow If this cannot be attained an intra-arterial infusion of blood is given during the critical period when the return flow of blood is greatly reduced

Especially interesting from a hemodynamic viewpoint are the interatrial septal defects and their surgical repair These defects are the most common cardiac anomalies of congenital origin In the presence of a defect in the septum between the two atria oxygenated blood may be shunted from the left atrium into the right atrium and unoxygenated blood may be shunted from the right to the left atrium The direction of the shunt flow depends upon the prevailing pressure gradient between the two atria The gradient varies in magnitude and may reverse its direction during the cardiac and respiratory cycle (Brecher and Opdyke 1950 Shaffer et al 1954) Due to the higher volume elasticity coefficient of the left atrial walls the mean pressure is higher in the left than in the right atrium (Little 1949) Therefore more blood is usually shunted from the left to the right atrium than in the opposite direction The shunted blood may greatly increase venous return to the right ventricle This puts an extra load on the right ventricle which has to eject the normally returning venous blood plus the shunted blood When the right ventricle fails to discharge the large amounts of inrushing blood the pressures rise in the right atrium Thereupon the shunt flow will reverse its direction and blood will pass from the right to the left atrium This may relieve the strain on the right ventricle (Brecher and Opdyke 1951) Thus the creation of an interatrial septal defect may relieve the right ventricle in conditions which cause a high resistance in the pulmonary bed (Leeds et al 1955)

Various methods have been developed for a repair of interatrial septal defects Venous return must not be embarrassed as a result of these procedures The choice of the method depends to a great deal upon the size and location of the defect and pathological changes of the outer atrial wall Bailey et al (1953) and Bailey (1955) developed the atrioseptopexy by which part of the pathologi

cally enlarged right atrial wall is used in order to cover the hole in the septum The rationale of this method is the use of an excess of cardiovascular tissue in the form of the usually distended right atrial wall for covering a lack of cardiovascular tissue in the septum (expressed by the defect) This method which conserves the atrial wall has the advantage of not restricting venous return from the caval veins Sondergaard Bjork and Crawford (see Lam 1955) use the circumclusion operation by which suitably located defects can be drawn together with a ligature The ligature is passed bluntly around the defect area through a cleavage line between the muscle layers of the two atria The procedure is relatively simple Right and left atria retain their shape and the inflow tracts to the heart are not blocked

Hemodynamically interesting is the atrial well operation by Gross and his colleagues (1953) and Gross and Watkins (1953) These authors utilize the fact that the veins represent a low pressure system They sew a soft rubber funnel to the right atrial wall incise the wall and permit the blood to rise in this well Right ventricular filling appears to be normal despite the wide open atrium The repair of the atrial septal defect is made directly (though not by direct vision) through the large wall opening Usually blood rises only a few centimeters in the well in accordance with the existing atrial pressure However if tricuspid regurgitation is associated with the interatrial septal defect atrial pressures have been found to rise so high that the well could not be applied (Watkins and Gross 1955)

Summarizing

In closed heart surgery venous return is usually blocked for short periods by the insertion of the operating finger and instrument in the narrowed passages of the inflow or outflow tracts The brief duration of the interference is generally well tolerated In interatrial septal defects return flow to the right ventricle is increased by the predominance of shunt flow from the left to the right atrium In the repair of interatrial septal defects particular care must be taken not to restrict caval inflow

Open Heart Surgery

Two methods hypothermia and extracorporeal circulation have been successfully employed to permit intracardiac surgery under direct vision They can be used alone or in combination with one another

In hypothermia the organism is suitably cooled to temperatures ranging between 28 and 30 C in order to reduce the metabolic needs of the tissues especially those of the nervous system and myocardium According to Berne (1954) hypothermia as employed in cardiac surgery does not seriously interfere with myocardial competence as such provided the natural slow rhythm of the heart is maintained By means of an arterial infusion of oxygenated blood the vital organs can be adequately supplied with oxygen during the critical period when the heart is open In order to enter the heart the caval veins and the azygos vein are clamped Surgical maneuvers may thus be performed under direct vision on the right heart for periods lasting from 6½ to 20 minutes (Bailey Cookson et al 1954) When hypothermia alone is used (without the

addition of an extracorporeal circulation or arterial blood infusion) the safe period of inflow stasis is limited to about 12 minutes (Gollan et al 1955) The marked congestion in the systemic veins as such does not appear to have a detrimental effect on the tissues (For a discussion on advantages and disadvantages of various methods of inducing hypothermia see Lam 1955 p 408)

Extracorporeal circulation has been employed in various forms to bypass parts of heart and great vessels or the entire heart If the heart is completely bypassed the cardiac chambers can be opened and intracardiac operations such as repair of an interatrial or interventricular septal defect can be performed under direct vision in a relatively dry field The effective working time within the heart can thereby be increased to 20 or 30 minutes

For bypassing the heart Lillehei and his co-workers (1955 see also for previous literature) have developed a method of controlled cross circulation which has proved to be very successful for the intracardiac surgery of normothermic patients In cross circulation blood is continuously circulated through tubes from one subject to another and back again Uncontrolled cross circulation has been described by Egdahl (1955) In applying the principle of controlled cross circulation to cardiac surgery one subject serves as a donor and the other is the patient Blood from the brachial artery of the anesthetized donor is passed through tubing via a finger pump (sigmamotor pump) to the aorta of the patient It perfuses the coronary arteries and other vital organs After passage through the patient's capillary beds the blood is collected from the superior and inferior caval veins and returned through tubing with the aid of a pump to the donor's veins After the cross circulation has started the right atrial inflow to the patient's heart is stopped by clamping the caval veins and a cardiotomy can be performed for direct vision surgery

It is obvious that such a system must be so balanced that exactly the same quantity of blood flows from donor to patient as from patient to donor Fluctuations in the patient's venous return especially may unbalance the system If less blood is returned from the patient to the donor than is pumped from the donor to the patient the anesthetized donor may become unnoticeably exsanguinated Hence the detection and immediate correction of *differences* in the two way flow is an important problem which must be solved before cross circulation can be generally applied with reasonable safety

In our laboratory we became recently interested in this problem and searched for a method of balancing the two way flow in cross circulation (Brecher et al 1955) In animal experiments cross circulation flow both ways was simultaneously measured with two bristle flowmeters (see Fig 15) A difference in the flow *rates* indicated an imbalance of the flow from donor to recipient and vice versa This method appears however rather complicated for use in the operating room Since the cardinal problem is a prevention of the donor's unnoticed blood loss we used the donor as a "cumulative flowmeter" by placing him during the entire cross circulation procedure on zero reading scale Thus inflow and outflow from the donor could be continuously monitored Blood loss from the donor could be accurately measured and replaced by intravenous infusion The experimental arrangement for cross circulation with the aid of donor's scales is illustrated in Fig 55 It appears that the use of scales solves simply and ac

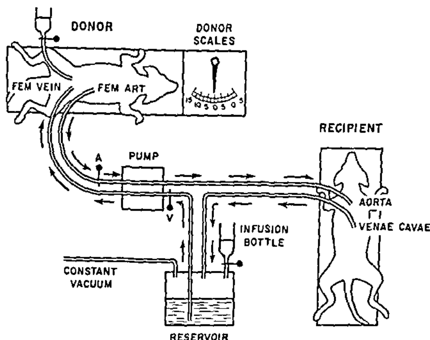


FIGURE 53 Diagram of controlled donor cross-circulation The two way blood flow from donor to recipient and vice versa is balanced with the aid of s l on which the donor is resting Suction from the reservoir on the caval veins of the recipient is kept mild in order to forstall venous collapse

curately the problem of regulating the two way blood flow during cross circulation under operating room condition

The fluctuations in venous return from the patient during cross circulation are rather unpredictable It has been observed in dogs and to a lesser degree in humans that the arterial blood pressure falls in the patient shortly after cross circulation has started Similar observations reported by Dodrill and his associates (1952) during a bypass of the right heart suggest that this phenomenon might be explainable on a reflex basis (inverse Bainbridge reflex) The removal of the normal distention of the atrium and great veins by the suction of the pump would initiate reflexly a slowing of the heart and a decrease in blood pressure by generalized vasodilatation

Apparently owing to neurogenic or chemogenic fluctuations in the patient s venomotor activity blood is sometimes pooled in the peripheral parts of the venous system during the course of the cross circulation When this occurs or the patient loses blood during the cardiotomy the pump cannot remove enough blood from the patient s veins and the two way flow of the cross circulation becomes unbalanced In order to make the venous blood flow to the donor independent of fluctuation in the recipient s venous return we found it best to drain the recipient s blood into a suitable reservoir From there it is pumped at a constant flow rate to the donor The reservoir is indicated in the lower center of Fig 53

The Sigmamotor pump which is generally used for cross circulation develops

a very high degree of suction If the cannulae from the caval veins of the patient lead directly to the pump it may happen that the caval veins collapse completely or intermittently during fluctuations of the patient s venous return Because in collapsible structures flow decreases with extreme degrees of suction (see Fig 25), less blood is returned after caval collapse via pump to the donor The complete closure of the pliable venous wall over the holes in the collecting cannulae may damage the cavae and may even create a vacuum in the tubing between the patient s veins and pump leading to a degassing and gas bubble formation in the blood It was found that the interposition of a reservoir avoids these difficulties If no reservoir is used judicious blood infusion into the patient s veins helps to prevent the onset of collapse and keeps the caval flow constant At any rate, with or without reservoir the degree of suction should be so adjusted that the patient's caval veins deplete optimally without entering the collapsed stage Using as a guide curve A of Fig 25 it is best to work at the highest portion of the curve before it flattens and declines to the right Blood pooling in the patient s veins can also be favorably counteracted by the use of mild vasoconstrictor drugs

The amount of blood necessary to perfuse the vital organs during cross circulation is far less than the patient s cardiac output Andreason and Watson (1952) and Cohen and Lillehei (1954) found that in dogs the needed amount corresponds approximately to the volume flow through the azygos vein (one tenth of the cardiac output) when the caval veins are clamped The term azygos factor has been introduced to characterize this amount The important factor responsible for the success of open vision intracardiac surgery is the low rate of volume flow which has been found sufficient to keep the anesthetized normothermic patient alive (about 12 to 25 per cent of the resting cardiac output)

The function of the donor in controlled cross circulation is to oxygenate blood for the perfusion of the patient whose heart and lungs are bypassed Since there is always an element of danger involved for the donor the future development of open cardiac surgery is directed toward a replacement of the donor by equipment for blood oxygenation The team working with Lillehei has again been leading in this direction

Campbell et al (1955) developed in animal experiments a rather simple method substituting for the donor an isolated dog lung Following this work heterologous lungs have been successfully used by Lillehei and also other surgeons for bypassing the heart and lung in patients during open vision cardiotomy

Warden et al (1955) (see also Lillehei et al 1955) developed a still simpler technique of perfusing child patients from a reservoir of previously collected ' arterialized venous blood ' By warming the arm of a blood donor local arteriovenous anastomoses are opened whereby the oxygen content of the collected venous blood is greatly increased During the perfusion of the patient the blood returning from the patient s caval veins is collected via a pump, in bottles If one could reoxygenate this blood in a simple manner within a reasonable period one could use it again for the perfusion of the patient and thereby keep the amount of pre collected blood relatively small Work on the development of a suitable 'bottle oxygenator is in progress It has been used successfully in 17 patients by Kay and Cross (1956)

Looking back on the development of the various methods of extra corporeal circulation for bypassing the heart and lungs it appears that the cycle of development is coming to a close with perfusion of the patient from bottles and re oxygenation of the patient s blood in the collection bottle The perfusion bottle and re oxygenation bottle are essentially a simplified version of the more complicated pump oxygenators (artificial heart lung) (See Jongbloed 1951 Clowes et al 1954 Kusserow 1955 Melrose 1955 Hayes et al 1955 Kirklin et al, 1955, Newman et al 1955 Dodrill et al 1955) Due to the fact that the technical development of the pump oxygenators was not yet sufficiently advanced for safe intracardiac open vision surgery Lillehei and his co workers developed the controlled donor cross circulation which will probably be replaced by the simpler bottle methods

Under all conditions whether cross circulation an isolated lung arterialized venous blood or a pump oxygenator are used due consideration should be given to the ' laws of the collapsible tubes when the patient s venous blood is collected

Summarizing

In open cardiac surgery under hypothermia the marked venous distension by backed up blood does not appear to have detrimental effects as long as the lowered metabolic needs of the tissues are taken care of In controlled cross circulation for direct vision intracardiac surgery blood flow must be accurately balanced in both direction from the donor to the patient and vice versa Balancing can be assured by placing the donor on scales during the operation Fluctuations in venous return from the patient may cause complete collapse of the venae cavae if the suction appplied is excessive The collapse of the patient s vena cava by strong suction should also be avoided in other techniques of extra corporeal circulation

Final Remarks

In considering the various factors which are responsible for the return flow of blood to the heart one may feel tempted to evaluate the importance of each factor on a percentage basis In doing so one would soon discover that, except for the ejecting force of the ventricles, each individual factor could be eliminated without altering appreciably the quantity of the returning blood and cardiac output However it would be fallacious to conclude from this observation that all factors but ventricular ejection are unimportant

This may be illustrated by the following example Kagan (1952) destroyed 70 to 80 per cent of the outer wall of the right ventricle by cauterization and discovered that the right heart still possessed a nearly normal compensatory action when the pulmonary artery was greatly constricted Venous pressures and apparently venous return were not altered after the cauterization Recent investigations have been interpreted as showing that the maintenance of the practically unimpaired function of the right heart must be attributed to the undestroyed portions of the myocardium (Rose et al 1955)

It would certainly be erroneous to deduce from the cauterization experiments that 80 per cent of the right ventricular wall is unimportant They only emphasized the fact that the heart possesses remarkable reserve powers These are important physiological factors of safety as succinctly pointed out in an editorial article by Alexander and Wiggers (1953) The factor of safety, a term used in engineering indicates the margin by which the strength of material or structure exceeds the actual working stress to which it is submitted in normal use

According to this concept the various components which normally contribute to the return flow of blood to the heart should also be looked upon in their entirety as essential factors of safety The combination and integrated action of all factors—the ventricular ejection the respiratory pump the systolic ventricular attraction the recently demonstrated diastolic ventricular suction the muscle pump and venomotor activity—widen the margin of safety which assures the adequacy of venous return under normal and abnormal conditions

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